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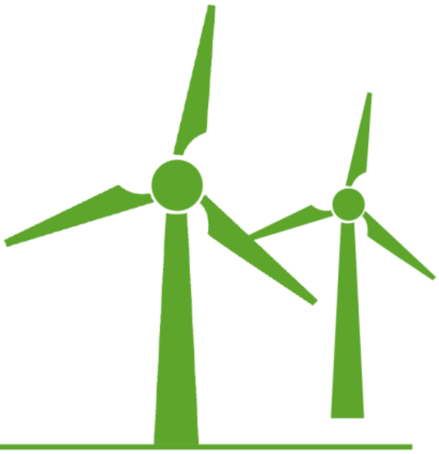
“Innovative business models for market uptake of renewable electricity unlocking the potential for flexibility in the industrial electricity use”

Simplified assessment methodology for optimal valorization of Flexible Industrial Electricity Demand



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List of abbreviations and acronyms

Belpex	BELgian Power EXchange
CHP	Combined Heat and Power
DRA	Demand Response Audit
GUI	Graphical User Interface
PP	Price Profile
ToU	Time of Use

Executive Summary

The main IndustRE project goal is to increase the use of flexibility in energy intensive industries to facilitate further market uptake of variable renewable energy through innovative business models and regulatory improvements. An important condition for a further deployment of flexibility in energy intensive industries is a simple, efficient and relatively accurate way to estimate the benefits of flexible operation of the industrial process. Even when there are attractive business models and there are no regulatory barriers, estimating the available flexibility potential and the associated economic value is currently often a time-consuming and complex undertaking.

A first step towards a simplified flexibility assessment methodology, is to simplify and structure the calculation of the economic value of flexibility into 3 contributing elements: a “flexibility model”, “price information” and a “calculation method”, as it has been proposed in [3]. The most cumbersome task is the construction of a flexibility model, which is typically the result of a two stage process: a “selection” and a “modelling” stage. During the selection phase, the technical installations are screened and a number of potentially relevant flexibility sources is chosen. During the modelling stage, models that describe the relationships between typical production numbers and electricity consumption, including typical limits and constraints, are constructed. This requires a wide spectrum of skills, from a good top-level understanding of industrial processes over a thorough understanding of energy flows to a deep understanding of modelling and optimization techniques. Hence, highly skilled staff is needed to calculate the economic value of flexibility, and consequently, the resulting overall cost of a Demand Response Audit creates a potential market entry barrier for many potential industrial flexibility (service) providers.

This report presents a simplified assessment methodology that aims at satisfying the following requirements:

- Being cost effective and time efficient
- Resulting estimations are of a sufficient order of magnitude accuracy for decision making
- No specific modelling and optimization knowledge and tools needed

A simplified assessment methodology can be seen as a first screening tool which focusses on the “ease of use” and as such plays an important enabling role of Flexible Industrial Demand. The main idea behind the simplified assessment methodology consists of mapping existing flexible industrial processes on a limited number of *normalized reference processes* by means of simple scaling and substitution rules. For normalized reference processes, the business cases are calculated in a lot of detail and the end result can be presented in a

graph, table, or in a more complex form in a graphical user interface. If the results are presented in a graph, we refer to this result as the *normalized business case graph*.

The possibilities and the shortcomings of the simplified methodology are illustrated in this report, by means of four business cases: time of use (ToU) pricing, day-ahead wholesale market optimization, imbalance price optimization and an on-site VRE business case for a single normalized reference process, which is chosen to be a generic battery model. Moreover, a practical example of a realistic industrial process is used to show how the normalized graph obtained for a generic battery model can be scaled to derive an estimate of flexibility value for a real industrial process.

The proposed methodology is very straightforward and accurate, and boils down to basic normalization, scaling and looking up a value in the corresponding normalized business case graph under the assumption that the industrial process can be mapped on a relevant reference process. Under the important assumption that a perfect mapping between the actual process and the reference process is possible, the simplified assessment methodology will deliver the same level of accuracy as the original method. This means that the obtained business case value is the best case value which provides an upper bound on the maximum achievable value for the given business model, based on historical data and without taking opportunity costs into account.

Nevertheless, it is impossible to foresee reference process which can handle the most complex industrial processes. Industrial processes are quite often an interconnection of underlying sub-processes where the complexity is caused by dependencies and constraints of the interrelations and less by the intrinsic complexity of the sub-processes itself. In this case, an approach could be only to consider the flexible processes individually, and calculate for each of them the value of flexibility. The total sum of these values will result in an overestimation of the real business case value. Nonetheless, this can still be very valuable information because it sets an upper boundary for the expected business case value

Furthermore, the simplified assessment methodology relies on the availability of public data. Although for some business cases, the lack of public data can be compensated by logical workarounds such as scaling (as e.g. for the ToU business case), such solutions cannot always be found. Besides for determining the potential value of the business case for the existing flexibility in the process, the results of the developed simplified method can be utilized for the purposes of (future) design of industrial processes for flexibility as well.

The document is non-exhaustive neither from the point of view of the covered business cases, target countries nor reference processes. The methodology may be further extended during the case studies which will be performed in WP4 of this project.

1 Introduction: The need and goal for a simplified assessment methodology

Background

The main IndustRE project goal is to increase the use of flexibility in energy intensive industries to facilitate further market uptake of variable renewable energy through innovative business models and regulatory improvements. The regulatory situation, suggestions for regulatory improvement, and a proposal for innovative business models have been investigated in the IndustRE project and reported in [1] and [2].

Even when there are attractive business models and there are no regulatory barriers, estimating the present flexibility and the associated economic value is not always straightforward. The estimation of the economic value of flexibility in an industrial process typically results in solving a constrained mathematical optimization problem which requires a decent flexibility model of the industrial process and relevant price information. Moreover, the optimization approach differs from business case to business case which introduces the need for different calculation methods.

It gets even more complicated when considering different EU member states because regulatory conditions, market frameworks and price structures and settings differ from Member State to Member State. Different data has to be used and even the calculation method can be different for the same business case in 2 different countries, which further complicates business case calculations.

A first step forward to simplify and structure the calculation of the economic value of flexibility, has been proposed in [3]. In [3], the business model calculation approach is logically organized in 3 contributing elements: a “flexibility model”, “price information” and a “calculation method”. The “flexibility model” describes the flexibility within the industrial process and is independent of the target country and/or selected business case, the “price information” and the “calculation method” are specific per business case and per target country. Quite attractive in the approach is that only a limited number of 4 calculation methods are sufficient to handle the most relevant business cases in the IndustRE target countries Belgium, France, Germany, Italy, Spain and the United Kingdom. Further, an “implementation matrix” is introduced which makes it easy to select the correct calculation method(s) for a specific business case in a particular country and indicates the availability of price information.

The need for a simplified assessment methodology

The approach in [3] mainly focusses on structuring and organizing price information and calculation methods. Probably the most cumbersome task, however, still remains: the construction of a “flexibility model”. A “flexibility model” is typically the result of a 2 stage process: a “selection” and a “modelling” stage.

The “selection” phase takes place during a “Demand Response Audit” (DRA) where a demand response expert visits the industrial installations. Together with the energy manager and technical experts of the industrial plant, the technical installations are screened from an electricity consumption point of view and a selection of “relevant” sources of flexibility is made. This activity is generally called the “Identification” step of the DRA.

In the “modelling” phase a flexibility model of the chosen production processes will be constructed as far as it is needed from an energy consumption point of view. The model describes in a simplified way the relationships between typical production numbers and electricity consumption including typical limits and constraints. The model is constructed by the demand response expert in close cooperation with the technical expert(s) of the industrial plant, typically a production engineer and an energy expert/manager. The resulting “flexibility model” is a translation of industrial process properties and limits into a mathematical constrained model which must have a format that can be interpreted by optimization software. This activity maps on what is generally called the “Quantification” step of the DRA.

The “selection” phase and the “modelling” phase require different skills from a demand response expert. For the “selection” phase, a good top-level understanding of industrial processes is needed in combination with a good understanding of energy flows. The “modelling” phase, however, requires thorough understanding of modelling and optimization techniques which are rather software and applied mathematics skills.

One of the goals of the IndustRE project is facilitating the use of Flexible Industrial Demand to improve uptake of variable renewable electricity. A crucial step to achieve this goal is the ability to estimate the economic value of a company’s flexibility in a quick and cost effective way. The above procedure is time consuming, requires highly skilled staff and consequently the resulting overall cost of a Demand Response Audit creates a market entry barrier for many companies. Simplifying this procedure and providing an easy to follow and apply methodology would make it more cost efficient and could turn this barrier into a market enabler.

The goal of a simplified assessment methodology

Although flexibility is present in many industries, building up interest in demand response is for most companies a long, time consuming, multi-stage process. It is a new way of thinking about energy consumption which requires changes in the processes, operational planning and strategic decision making.

Energy optimization is not the core activity of most industries: energy is mostly seen as a resource with a cost and the potential cost savings of flexible energy consumption is not considered. Especially in companies where the electricity cost component is limited in the overall operational cost structure, many plant operational decision makers will consider these changes as a risk for the continuity in the activities and are reluctant to accept additional constraints.

In many cases the interest in the possibilities of demand response is initiated by a limited number of people in the organization who need leverage to make steps forward within the company. Especially in the beginning of a transition process, an extended (and expensive) Demand Response Audit (DRA) is often difficult to get on the agenda. An important step forward could be made by offering the industries a simple, cost effective but reliable way to estimate an “order of magnitude” of what the financial benefit of demand response could be.

Further, it would be interesting that such a service could be offered by consultancy agencies and service companies which already have existing and strong links with the industries. Once consultancy agencies and service companies are aware of and capable to assess the techno-economic potential of flexibility, they could raise (further) interest for demand response at their existing and new industrial customers. Consultancy agencies offering e.g. energy and energy efficiency advice or engineering services. have a prominent position in the industry and are well placed to introduce the possibilities of demand response. They have a good understanding of the industrial processes and with a minimum of training they could take a good position to help industries in the “selection” of industrial processes with a high potential for flexibility.

While the “selection” task can be handed over relatively easily to existing consultants readily available in the industry, the “modelling” and “optimization” task requires skills which are less obvious to find. For that reason, it is important to offer these companies a tool which eliminates the use of specialized simulation and optimization software in favor of relatively simple/standardized tools (GUI, spreadsheet, graphs…).

Based on the above reasoning, the requirements for a simplified assessment methodology can be summarized as:

- Being cost effective and time efficient
- Resulting estimations are of a sufficient order of magnitude accuracy for decision making
- No specific modelling and optimization knowledge and tools needed

A simplified assessment methodology can be seen as a first screening tool which focusses on the “ease of use” and as such plays an important “enabling” role for Flexible Industrial Demand.

This deliverable presents a methodology which aims to fulfill the above requirements. The approach consists of mapping existing flexible industrial processes on a limited number of normalized reference processes by means of simple scaling and substitution rules. For normalized reference processes, the business cases will be calculated in great detail and the end result can be presented in a graph or spreadsheet. Starting from the business case result of a normalized reference process, the business case value of the real process can be calculated with some simple scaling rules.

The objective of this deliverable is to explain the concept of the “simplified assessment methodology” and to illustrate the approach. By means of a couple of examples, the potential of the methodology will be explained. This deliverable has not the intention to be “complete” and cover all possible business cases and all possible industrial processes, and does not serve as documentation of the developed methodology. This report should provide the reader with an understanding of the concept of the simplified assessment methodology, the approach followed as well as it envisions to explain and illustrate the way the methodology can be used by means of concrete examples. Depending on the needs, the methodology may be further extended during the case studies which will be performed in WP4 of this project.

Chapter 2 describes the concept of normalized reference processes and shows some examples of how the mapping between a real process and the reference processes works. In chapter 3, the concept of normalized business case graphs is explained. Finally, chapter 4 concludes the report.

2 Reference processes

2.1 Introduction

As explained in [3] and summarized in the introduction of this document, a demand response business case calculation typically boils down to constructing a simplified mathematical model of the industrial process. This model is then used in a mathematical optimization software tool to calculate the economic value. An important requirement for the simplified approach is that the modelling and optimization step can be avoided.

An initial possible approach could be to make a large database of industrial processes with calculated business cases. In that case, a simplified approach could consist of selecting an industrial process from the database which gets the closest and copy the according business case result. The nice property of the approach is that no model has to be made and no optimization has to be performed, but it is clear that the large diversity in industrial processes in nature and scale makes such an approach in practice very difficult, if not impossible.

Nevertheless, the underlying principle in the simplified approach described in this document is based on the above idea: pre-calculating business cases and derive results for other industrial processes from these pre-calculations. To make this work, two additional principles are introduced: “normalization” and “mapping on reference processes”.

Normalization and scaling

Some business case properties scale very well. For example, where battery storage is used to create a demand response business case, it is obvious that doubling the battery capacity and doubling the maximum (dis)charging power will result in a business case which makes the double amount of money. A “normalized” (e.g. 1 MWh storage capacity and charging power of 1 MW) battery storage business case is pre-calculated and other battery size business case results can be derived from that one single business case result. This will reduce the number of pre-calculated business cases enormously. Normalization and scaling properties of business cases are mainly addressed in chapter3.

Mapping on reference processes

Some industrial processes seem to be very different from a battery, but the underlying fundamental principle to create flexibility is the same. Some examples are very obvious: the ability to switch off a 1 MW device for 1 hour generates flexibility and whether this device makes hot water, steel plates or cookies does not matter. In all 3 cases the underlying "reference process" which generates the flexibility is the same and could be called a "schedulable load".

The simplified assessment methodology assumes that a large number of industrial processes can be mapped on a reduced number of reference processes. Once these reference processes are in place, the "modelling" phase of the flexibility model can be avoided and replaced by a "mapping" phase where the demand response expert has to select the best matching reference processes instead. This task/activity is considered more in reach of consultancy agencies and service companies than a "modelling" and "optimization" task.

Reference processes will be normalized and for each reference process a set of business cases will be pre-calculated. By means of "mapping" and "scaling", it is expected that the business case value for a broad range of industrial processes can be derived from a limited set of pre-calculated business cases.

This chapter does not have the ambition to describe all possible reference processes but tries to show the potential of this "mapping" approach by means of the example reference process which is described in the next section.

2.2 Example reference process

In this section, a generic battery model will be introduced as a an example reference process. Next, it will be shown how a buffered industrial process and a CHP with a hot water storage tank can be mapped on a the generic battery model.

2.2.1 Generic battery model

In many flexible processes, some sort of buffer is used. In some cases the buffering is direct under the form of electrical energy (battery), in some cases it is indirect (intermediate product, heat, …). In the following, it is shown that a battery model can be used to estimate the flexibility of other buffered processes by means of a mapping or substitution exercise. In this section, the "generic battery model" is described and in the next sections, 2 mapping or substitution examples are shown.

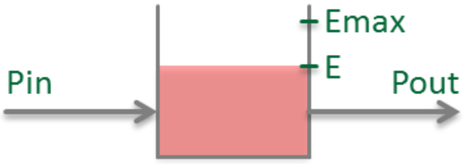


Figure 1: Schematic representation of the generic battery model.

Figure 1 shows a schematic representation of a generic battery model. It is a “conceptual” battery which is basically an electricity buffer which can store electricity.

Inputs/outputs of the battery:

- **Pin**: is the actual charging power of the battery [kW].
- **Pout**: is the actual discharging power of the battery [kW].

State:

- **E**: actual energy stored in the battery [kWh]

Parameters:

- **Emax**: maximum energy which can be stored in the battery [kWh]
- **Pin_max**: maximum value of Pin [kW]
- **Pout_max**: maximum value of Pout [kW]
- **n**: round trip efficiency of the battery. This parameter expresses the conversion losses of the storage process.

Equations:

- dE/dt = Pin – Pout/n

The behavior of the buffer is described with the above equation, with t the time in [s]. The equation expresses that the energy increases when power enters the battery and that the energy drops when power leaves the battery.

Constraints:

- 0 ≤ Pin ≤ Pin_max
- 0 ≤ Pout ≤ Pout_max
- 0 ≤ E ≤ Emax

The above constraints express that charging and discharging is constrained by a maximum power and that the battery has a limited storage capacity.

2.2.2 Mapping on a buffered industrial process

In this section, the generic battery model will be mapped on an industrial process which is shown in Figure 2. The figure represents an industrial process which is split in 2 parts:

- The first part of the process (1) contains a lot of flexibility and the output rate of this part is proportional with the electrical power which is consumed in (1)
- The second part of the process (2) has no flexibility and requires a constant feed of the product.

Both parts of the installation are decoupled by means of a buffer (3), where the intermediate product can be stored. The first part of the installation can do whatever it wants as long as the buffer upper and lower limits are not exceeded.

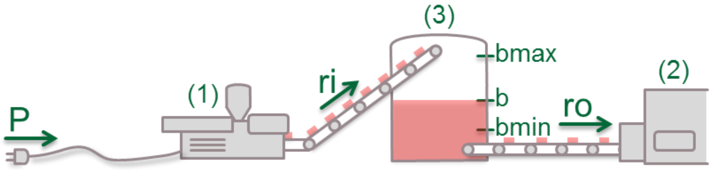


Figure 2: Schematic representation of a buffered industrial process.

This setup behaves quite a bit different compared to a battery system. A battery can “consume” electricity while charging and “produce” electricity when discharging. This setup can only “consume” electricity but the example will show that an appropriate set of substitutions can make this installation “virtually” behave as a battery.

In the equations below, only the electricity consumption of the first part will be considered because that is the only part which contains flexibility.

Inputs/outputs:

- **P**: actual electrical power of the industrial process [kW]
- **ri**: production rate of the industrial process before the buffer [kg/h]
- **ro**: production rate of the industrial process after the buffer [kg/h] which is assumed to be constant

State:

- **b**: filling state of the buffer [kg]

Parameters:

The parameters only described the process properties before the buffer and the buffer itself:

- **K:** power constant of the industrial process before the buffer [kg/kWh]
- **bmin:** minimum level of the buffer [kg]

- **bmax:** maximum level of the buffer [kg]

Equations:

- ri = P.K
- db/dt = ri-ro

The first equation expresses that the electricity consumption of the flexible process is proportional with the production rate. The second equation expresses that the buffer level changes when the input rate and output rate are different.

Constraints:

- bmin ≤ b ≤ bmax
- Pmin ≤ P ≤ Pmax

The first constraint expresses that the buffer level should stay between a certain minimum and maximum level. The second constraint expresses that the industrial process between a certain minimum and maximum power.

Substitutions:

By means of the following substitutions, the above equations can be mapped on the equations of the generic battery model (see section 2.2.1):

- n = 1
- Pin = (ri - ro) / (2·K)
- Pout = (ro - ri) / (2·K)
- E = (b - bmin) / K
- Emax = (bmax - bmin) / K
- Pin_max = Pmax –ro/K
- Pout_max = ro/K - Pmin

In the above equations, the left argument always refers to a parameter/input/output/state of the generic battery model, the right argument uses parameters/inputs/outputs/states of the buffered industrial process. Pout_max is a generic battery model property and should not be confused with the power of process after the buffer, which is not considered in the calculations. In this specific case, the round trip efficiency is set to 1 because we consider there are no losses in the buffer.

A practical example:

In the above equations, constraints and substitutions seem quite abstract, but a simple example will show how this works in a more practical way.

Assume a polypropylene pelletizer production line with a pelletizer which can be modulated between 30 and 100 %. The pelletizer has a maximum production capacity of 20 ton/h and has an electricity consumption of 200 kWh/ton. At the maximum production level, the pelletizer consumes 4 MW. The polypropylene pellets are stored in a bulk storage silo with a maximum capacity of 500 ton. For production security reasons the minimum capacity in the storage silo should not be lower than 100 ton. The buffer feeds the rest of the production process and has a constant feed of 14 ton/h.

- ro = 14.000 kg/h
- K = 1000[kg/ton]/200[kWh/ton] = 5 kg/kWh
- bmin = 100.000 kg
- bmax = 500.000 kg
- Pmin = 1.200 kW
- Pmax = 4.000 kW

With the above substitutions, the flexibility of the above production facility can be mapped on the flexibility of a battery with the following parameters:

- Emax = 80 MWh
- Pin_max = 1.2 MW
- Pout_max = 1.6 MW

Emax represents the energy difference between the highest and lowest buffer levels. In tons the difference is 400 ton which requires 80 MWh of energy. Pin_max corresponds in practice with the maximum fill rate of the silo. This happens when the pelletizer runs at maximum capacity. Keeping in mind that there is a constant feed into the rest of the production process, the net maximum fill rate of the silo is 20 ton/h – 14 ton/h = 6 ton/h which corresponds with an electricity consumption of 1.2 MW. Similarly, Pout_max corresponds with the maximum emptying rate of the silo which happens when the pelletizer runs at minimum capacity. The net maximum emptying rate of the silo is 14 ton/h – 0,3 x 20 ton/h = 8 ton/h which corresponds with an electricity “discharging” of 1.6 MW.

2.2.3 Mapping on a CHP with a hot water storage tank

In this section, the generic battery model will be mapped on a combined heat and power (CHP) unit which generates electricity and heat at the same time. It is assumed that the CHP is combined with a hot water storage tank as shown in Figure 3.

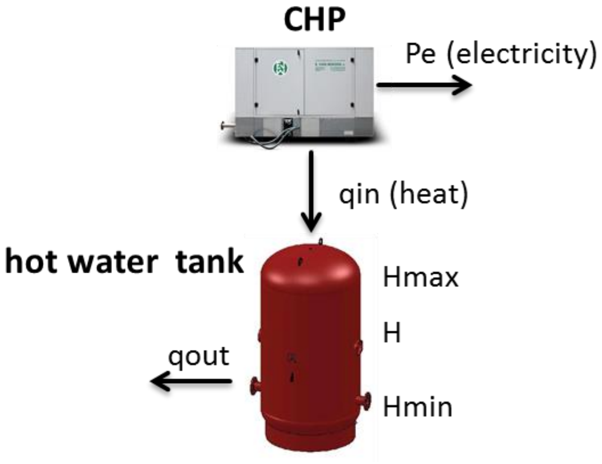


Figure 3: Schematic representation CHP in combination with a hot water storage tank.

It is assumed that the CHP can be modulated in a certain range (typically from 65 … 100%) and that the ratio between heat and electricity is constant. The heat of the CHP is buffered in a hot water storage tank and a constant hot water offtake is assumed. In principle, this setup behaves exactly the opposite of a battery system. In a battery, when more electric power is injected in the electricity system, the energy level in the battery will decrease. In this setup, when more electric power is injected in the electricity system, the energy level in the hot water storage tank will increase. Again, with an appropriate set of substitutions, the behaviour of this setup can be mapped on a “virtual” battery.

Inputs/outputs:

- **Pe**: electrical power generated by the CHP [W]
- **qin**: thermal power generated by the CHP [W] which enters the hot water storage tank
- **qout**: thermal power consumption [W] used by the rest of the plant. For the sake of simplicity, qout is assumed to be constant.

State:

- **H**: hot water energy level in the hot water storage tank [J]

Parameters:

- **K:** thermal/electric power ration of the CHP [-]
- **Hmin:** minimum energy level in the storage tank [J]
- **Hmax:** maximum energy level in the storage tank [J]

Equations:

- $qin = Pe.K$
- $dH/dt = qin-qout$

The first equation expresses a fixed ratio between the electricity and the heat production. The second equation expresses that the energy level in the storage tank changes when the thermal input and output power to the storage tank are different. It is assumed that thermal losses of the tank are negligible.

Constraints:

- $Hmin \le H \le Hmax$
- $Pe\_min \le Pe \le Pe\_max$

The first constraint expresses that the energy level in the hot water storage tank should stay between a certain minimum and maximum level. The second constraint expresses that the electrical output power of the CHP is physically restricted between a certain minimum and maximum power.

Substitutions:

By means of the following substitutions, the above equations can be mapped on the equations of the generic battery model (see section 2.2.1):

- $n = 1$
- $Pin = (qout - qin) / (2.K)$
- $Pout = (qin - qout) / (2.K)$
- $E = (Hmax - H) / K$
- $Emax = (Hmax - Hmin) / K$
- $Pin\_max = qout/K – Pe\_min$
- $Pout\_max = Pe\_max – qout/K$

As in the previous example, the left argument always refers to a parameter / input / output / state of the generic battery model, the right argument uses parameters / inputs / outputs

/ states of the buffered industrial process. Also in this case, the round trip efficiency is set to 1 because the thermal losses in the tank are assumed to be negligible.

A practical example:

A pharmaceutical company has a CHP with a maximum electrical power of 400 kW which converts 40 % of its total power in electricity and 60 % in thermal power. The CHP can be modulated between 65 % and 100 % of its maximum capacity. The CHP feeds the hot water in a 15.000 l hot water storage tank at 90°C, the inlet water has a temperature of 15°C. The pharmaceutical company needs about 10.000 l/h of hot process water at a temperature of 60°C which is achieved by mixing water of 90°C with cold inlet water of 15°C. The storage tank should always have a minimum of 10 % of hot water.

- qout = 10.000[l/h] / 3600[s/h] x 1[kg/l] x (60-15)[K] x 4186[J/(kg.K)] = 523 kW
- K = 60% / 40% = 1.5
- Hmax = 15.000[l] x 1[kg/l] x (90-15)[K] x 4186[J/(kg.K)] = 4.709 MJ
- Hmin = 10% x Hmax = 471 MJ
- Pe_min = 400[kW]*65% = 260 kW
- Pe_max = 400 kW

With the above substitutions, the flexibility of the above production facility can be mapped on the flexibility of a battery with the following parameters:

- Emax = (Hmax - Hmin) / K = 2825 MJ = 784 kWh
- Pin_max = 89 kW
- Pout_max = 51 kW

In the above calculation, it becomes clear that there is a significant difference between Pout_max and Pout_min. In “virtual” battery terms this means that the battery can be charged faster than it can be discharged. In CHP terms this means that the permanent need of process water is high. On average a thermal power consumption of 523 kW is needed. This corresponds with an average electricity production of 523/1.5 = 349 kW which can be considered as the electrical base production of the CHP. The maximum power of the CHP is 400 kW, so compared to that base production the CHP can inject an extra 51 kW which maps on the battery Pout_max of 51kW. Similarly, the minimum electrical power of the CHP is 260 kW which is 89 kW lower than the base production.

3 Normalized business case graphs

3.1 Introduction

In the previous chapter, the concept of reference processes and mapping was explained. For the reference processes, business cases will be pre-calculated in a way that they can easily be re-used for other business cases. The concept will be explained in this chapter using the generic battery model as a reference model.

In the next section the concept of normalized business case graphs will be explained by means of an example. In the subsequent sections, the developed simplified assessment methodology is illustrated by several examples of business cases. There are three business case examples for which the normalized business graph is presented and discussed in detail: standard contract optimization (and within this group in particular time of use (ToU) pricing), day-ahead wholesale market optimization, and imbalance price business case. Next to these business cases, a practical example from Section 2.2.2 is utilized in section 3.6 to demonstrate the use of normalized business case graphs.

3.2 The concept of normalized business case graphs

Normalization

In this section, the concept of a normalized business case graph will be explained by means of an example. The generic battery model will be used to show how a normalized day-ahead business case graph is constructed. This will be done with the model, as explained in section 2.2.1, with the following settings:

- Emax = 1 MWh
- Pin_max = 1 MW
- Pout_max = 1MW
- n = 1

The battery is connected to the electricity grid and can buy and sell electricity on the day-ahead market. By charging (buying) at cheap moments and discharging (selling) at expensive moments, profit can be made.

By means of the Price Profile (PP) optimization method [3], the optimal charging and discharging patterns are determined. In the beginning of the optimization, the battery is considered half-full and there is an additional constraint that the battery should be half-full again at the end of the considered time horizon (a day in this example).

Figure 4 shows the result for a single day optimization on the day-ahead market. During the optimization it is assumed that the day-ahead market price is known. On that particular day, the day-ahead price varies between 10 €/MWh and 70 €/MWh. It is clearly seen that the battery is charged when the price is low and that the battery is discharged when the price is high. In this particular example a total profit of 66,16 € could be made for that particular day of day-ahead trading. The value is only representative for that particular day and will vary from day to day. In order to get a more representative value it makes sense to do the same optimization but for a whole year. For this particular year the total profit would have been 19.240 €/year or an average a profit of 2.2 €/h.

The above results scale very well with the battery size, in- and output power. In case Emax, Pin_max and Pout_max are doubled, the profit will double as well to an average of 4.4 €/h so there is no need to repeat the business case calculation for other Emax, Pin_max and Pout_max as long as all properties are multiplied with the same factor. For that reason, the above result can be “normalized” by dividing all parameters by Pin_max: the profit of a battery on the day-ahead market is 2.2 €/MW/h. In the remainder of this document, the business case profit will be expressed in €/MW/h because it allows an easy comparison with published average availability prices for reserves which are often expressed in €/MW/h as well [4],[5].

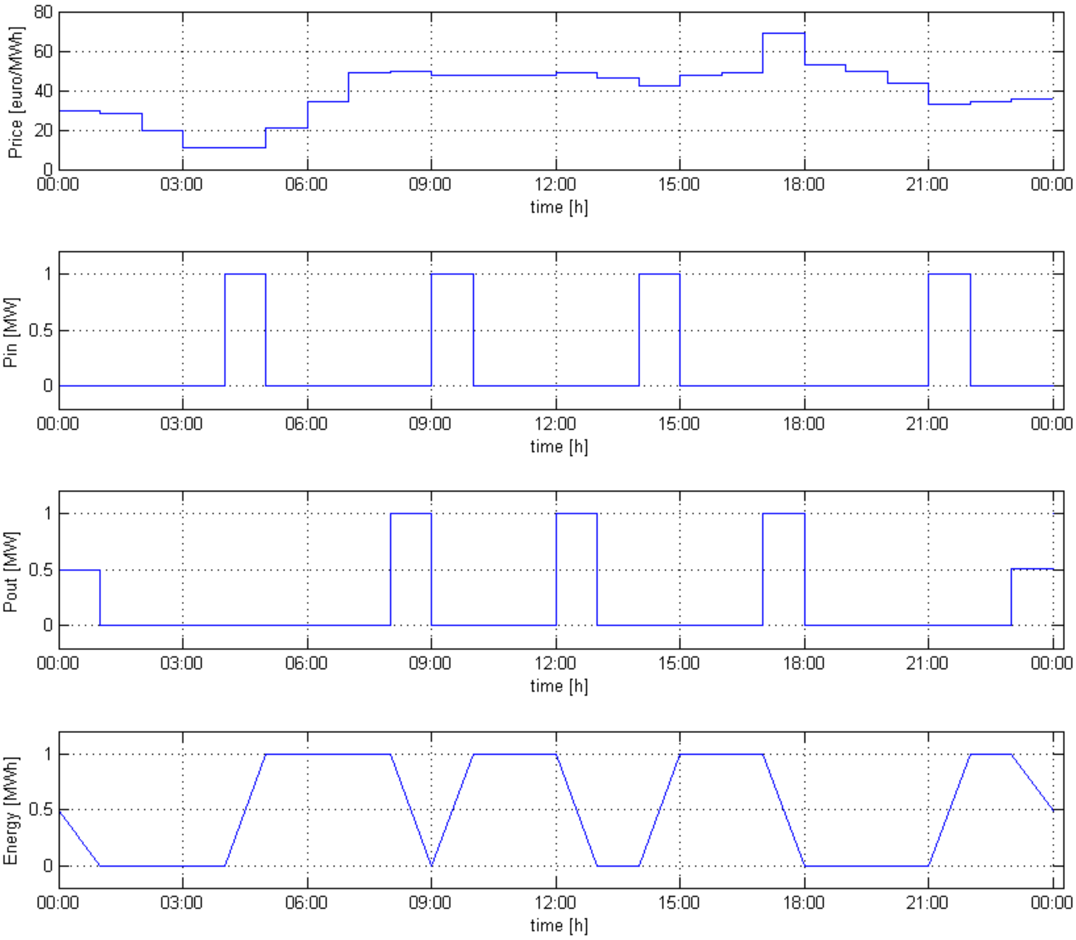


Figure 4: Optimal charging and discharging strategy for a 1 MWh battery on the day-ahead market for a given day. The upper plot shows the varying day-ahead price, the second plot shows the moments in time when the battery is charging, the third plot shows the moment in time when the battery is discharging and the lower plot shows the energy status of the battery

Normalized business case graph

Normalization only works when all battery parameters are increased proportionally. Running a new business case simulation with the double value for Emax = 2 MWh, but keeping Pin_max and Pout_max = 1 MW results in an average profit of 3.68 €/MW/h which is less than the double value. For that reason a series of business case calculations have to be done with varying value of Emax.

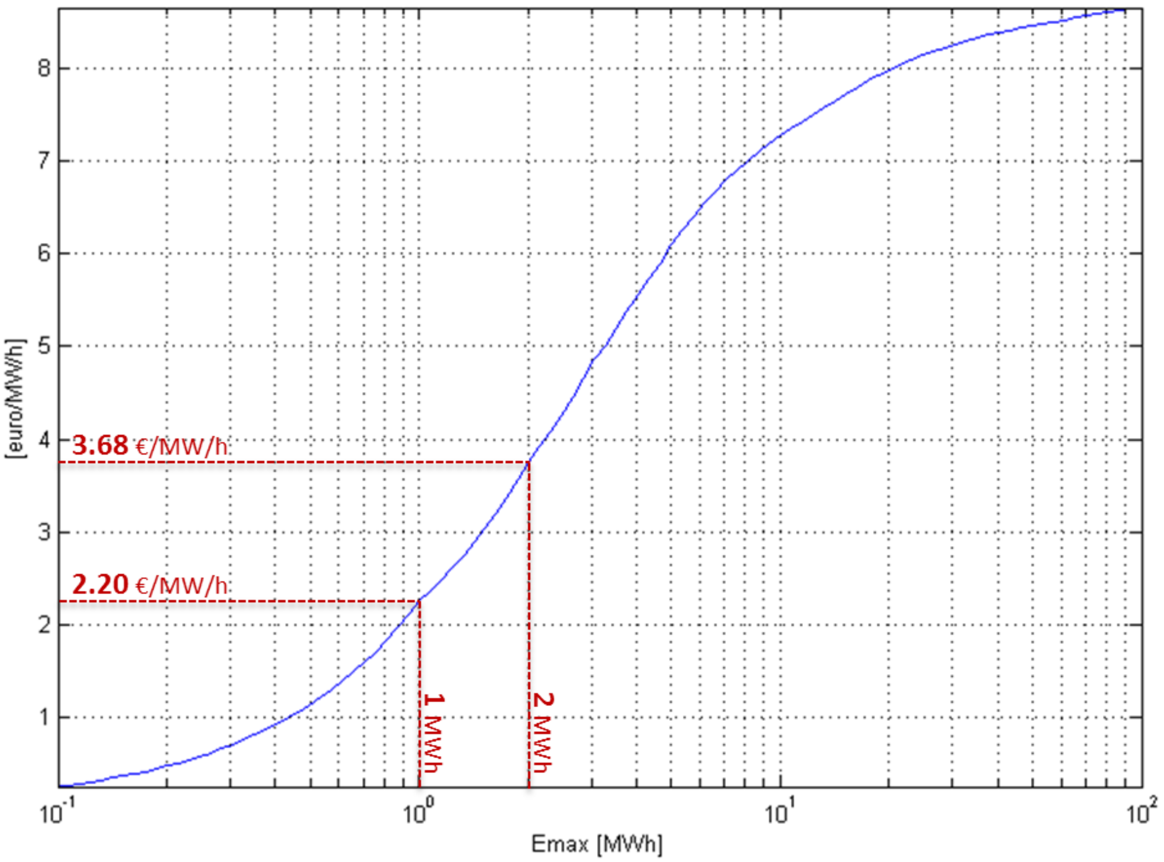


Figure 5: Normalized day-ahead business case graph for the generic battery reference model. The graph expresses the normalized business case profit as function of a varying battery size.

The result of the business calculations is shown in Figure 5. The graph shows the evolution of the normalized profit as function of a varying battery size. From the graph, the earlier business case calculation examples can be derived easily at 1 and 2 MWh. By representing the series of business case calculations in a graph in combination with the scaling property, a large set of business case can be represented in a single line graph as shown in Figure 5.

Since this section only focusses on the concept, the detailed discussion of Figure 5 will be done in section “3.4 Day-ahead market business case graph”.

3.3 ToU business case graph

In this section, a normalized business case graph is shown and analyzed for the business case of standard contract optimization, and within this group in particular for the time of use (ToU) pricing. For this business case, the price profile calculation method (including energy and peak component) as explained in [3] is applied.

The normalized business case graph is obtained from optimization of the energy consumption over a given time horizon so that the energy costs are minimized for the given price profile and the generic battery flexibility model. Throughout all examples in this section, the parameters of the generic battery flexibility model are the following (unless stated otherwise):

- Pin_max = 1 MW
- Pout_max = 1 MW
- n = 1
- Emax = variable, 0.1 – 60 MWh.

The energy costs have two components: the electrical energy component (for which the price is expressed in €/MWh), and a peak consumption component (for which the price is expressed in €/MW/month).

The peak price, λ_C (or capacity price in €/kW/month) is highly dependent on the connection point of the considered flexibility source. In Belgium, the peak price for consumption typically varies from 0,97 €/kW/month to 14,94 €/kW/month [6], depending on the voltage level of the considered network.

In the ToU business case, a typical price profile consists of two periods: a period of low electricity price, and a period of high electricity price. The difference between the two has a direct impact on the value of flexibility, whereas the exact low and high electricity ToU price values have no impact on the flexibility value. Therefore, we introduce the notion $\Delta\lambda_{TOU}$ to be used further on, which will be used to define the difference between the low and high ToU tariff. Another important aspect of ToU prices is the duration of the period of high and low prices. This as well has a direct impact on the value of flexibility, as will be shown below.

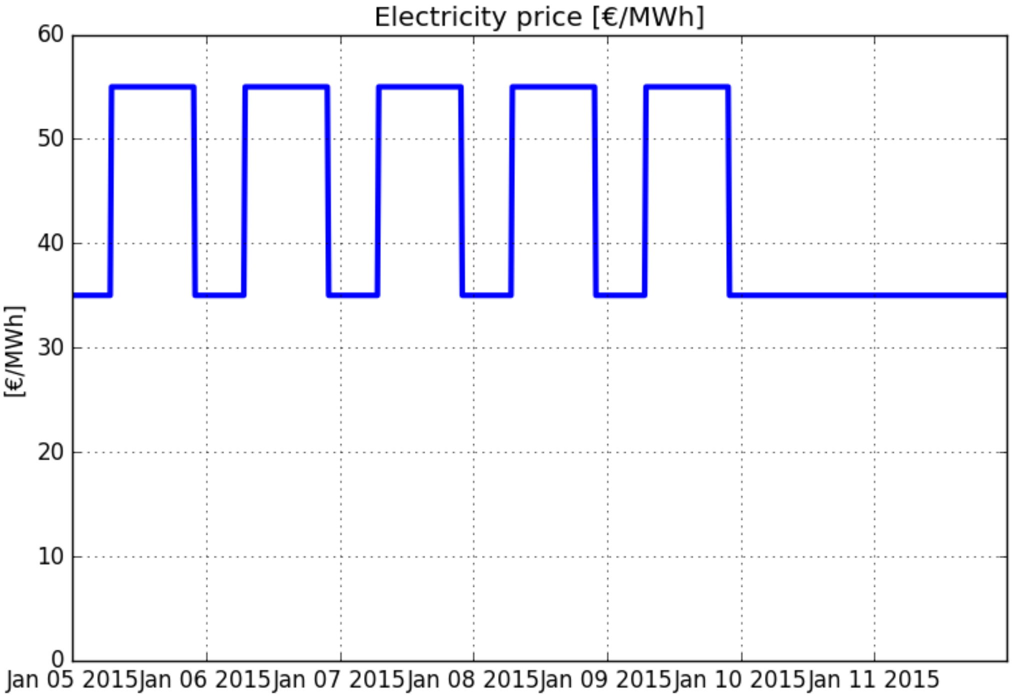


Figure 6 A representative ToU weekly profile. On the weekdays, the price is high between 7am and 10pm, and it is low at all the other periods. The values of low ToU price of 35 €/MWh and high ToU price of 55 €/MWh are chosen to illustrate a possible realistic case, but they do not reflect any particular specific contract.

For illustrative purposes of this deliverable, a representative ToU price profile as shown in Figure 6 is chosen. On the weekdays, the price is high between 7am and 10pm, and it is low at all the other periods. The values of low ToU price of 35 €/MWh and high ToU price of 55 €/MWh are chosen to illustrate a possible realistic case, but they do not reflect any particular specific contract. The ToU price difference $\Delta\lambda_{TOU}$ might be smaller or larger for some industrial processes, depending on the specific energy contract.

To summarize, the notion λ_C will be used in this section for the peak price, in accordance with the notion introduced in [3]. The notion $\Delta\lambda_{TOU}$ will be used to define the difference between the low and high time of use (ToU) tariff.

This section is further organized as follows: first, the business case without peak pricing component is analyzed including the business case sensitivity to differences in the price between the low and high ToU tariff $\Delta\lambda_{TOU}$. Next, the business case is extended with the peak price component and the sensitivity to the different peak prices is presented.

3.3.1 Business case graph without peak pricing

The business case graph is calculated for the differences in the price between the low and high ToU tariff $\Delta\lambda_{TOU}$ = 20 €/MWh, which is shown in Figure 6, and peak price λ_C = 0 €/MW. The graph is presented in Figure 7 for the generic battery sizes up till 60 MWh.

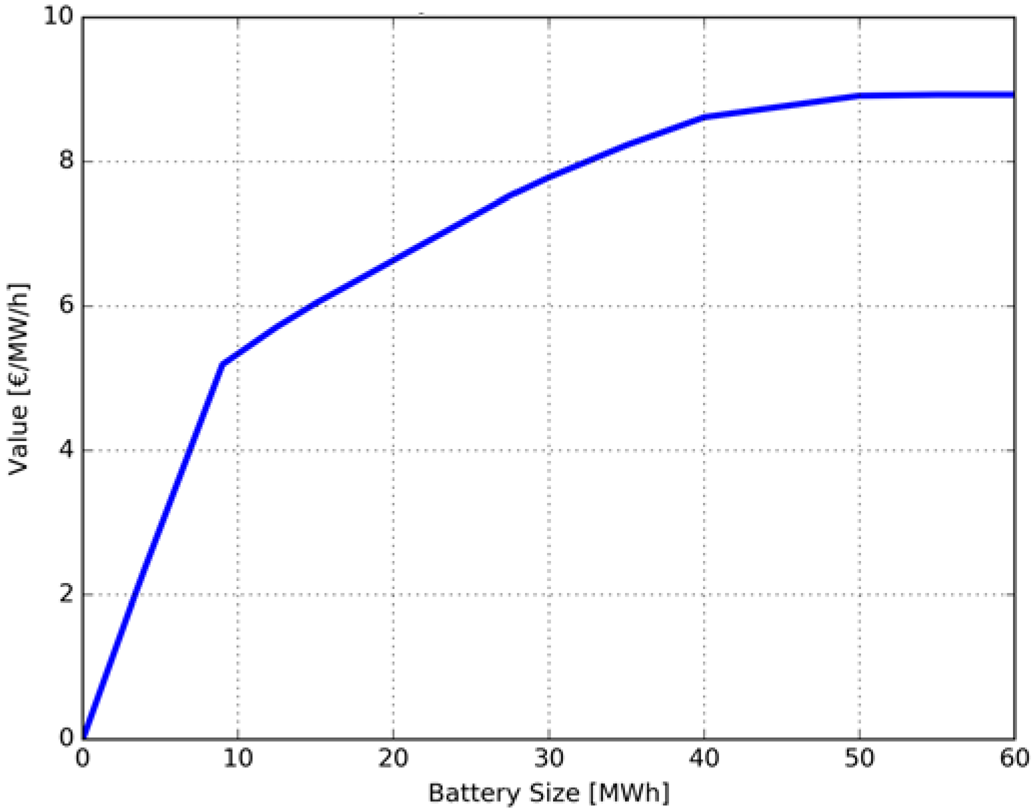


Figure 7 Normalized business case graph for ToU pricing with a price difference between the low and high ToU tariff $\Delta\lambda_{TOU}$*.= 20 €/MWh and peak price* λ_C *= 0 €/MW.*

The normalized business case graph contains two characteristic points: at the generic battery size of 9 MWh, there is an inflection point, and there is also a saturation point, after which the normalized flexibility value does not increase.

These points are closely related to the shape of the electricity price over time (see Figure 6). The optimization objective is constructed so that it is always more profitable to consume electrical energy during low ToU price hours. This particular example was inspired by the Belgian situation where during the weekdays, the period of low ToU prices lasts from 22.00h until 7.00h the next day, which is in total 9 consecutive hours of low electricity prices compared to high ToU prices outside this period for weekdays. As the maximum input power in the battery is 1 MW, it is expected that the value of flexibility increases linearly with the increase of generic battery size until the size of 9 MWh is reached. This can be clearly observed in Figure 7.

When the generic battery size is increased beyond the size of 9 MWh, the flexibility value keeps on increasing as the flexibility owner can capture more of the longer ToU low price periods during weekend, however, the increase in flexibility value is not linear. The increase in flexibility value becomes smaller and smaller as the saturation point approaches. Once the battery size becomes so large that the whole period of the low TOU price during the weekend can be stored, the value of flexibility cannot be further increased with the increase of the battery size. Therefore, a saturation point is reached, which can also be observed in Figure 7.

The duration of the high ToU tariff, which was here chosen to be between 7.00 and 22.00, can vary from country to country, or even from one electricity provider to another. Nevertheless, the same phenomena as shown and explained on an example for ToU prices given in Figure 6 will occur. For instance, a ToU contract with a high ToU tariff assigned to a period between 8.00 and 23.00, or 6.00 and 21.00 on weekdays will result in an identical normalized flexibility value business case graph as shown in Figure 7, because the duration of the low price tariff overnight and during the weekend is identical in all three examples.

Although slightly less common, there are also contracts with three different tariffs and three accompanying tariff periods. Following the same procedure, normalized business graph for ToU pricing with three tariff structure can be calculated.

Lastly, note that it is not necessary to know the exact low and high ToU price values in order to estimate the value of flexibility by this method. As explained in [3], the value of flexibility is obtained from the generated added value obtained as a difference in the case when flexibility was optimally utilized compared to the case when no flexibility was employed. Due to this subtraction, the only information that matters is the difference in ToU price values ($\Delta\lambda_{TOU}$), and not the exact price levels. In other words, price profiles as shown in Figure 6, or a price profile shaped in the same way, but with the low ToU price of 80 €/MWh, and high ToU price of 100 €/MWh result in exactly the same normalized business case graph shown in Figure 7.

Graph scaling property 1: Pin_max scaling

The graph in Figure 7 is generated for Pin_max equal to 1 MW. In case Pin_max is different from 1 MW, the graph can still be used. The actual business case value is calculated as:

- Value = Value_norm . Pin_max

Value_norm is the normalized business case value found in the graph at Emax_norm, with:

- Emax_norm = Emax / Pin_max

<u>Numerical example</u>: suppose a battery with size of 8 MWh and a maximum charging power of 0.4 MW.

- Emax_norm = 8 / 0.4 = 20
- Value_norm = 6.7 €/MW/h (see Figure 7)
- Value = 6.7 x 0.4 = 2.68 €/h

With an 8 MWh battery and a maximum charging power of 0.4 MW, an average profit of 2.68 €/h can be made.

Graph scaling property 2: $\Delta\lambda_{TOU}$ *scaling*

In the previous section, it was shown that the normalized business case graph for ToU pricing is highly dependent on the shape of the ToU price over time. Moreover, in the implementation matrix, as presented in [3], it is indicated that, in general, the price information from the ToU contract is sensitive and hardly available. Therefore, in this section, the scalability of the normalized business graph for ToU pricing as a function of different $\Delta\lambda_{TOU}$ price differences is explored.

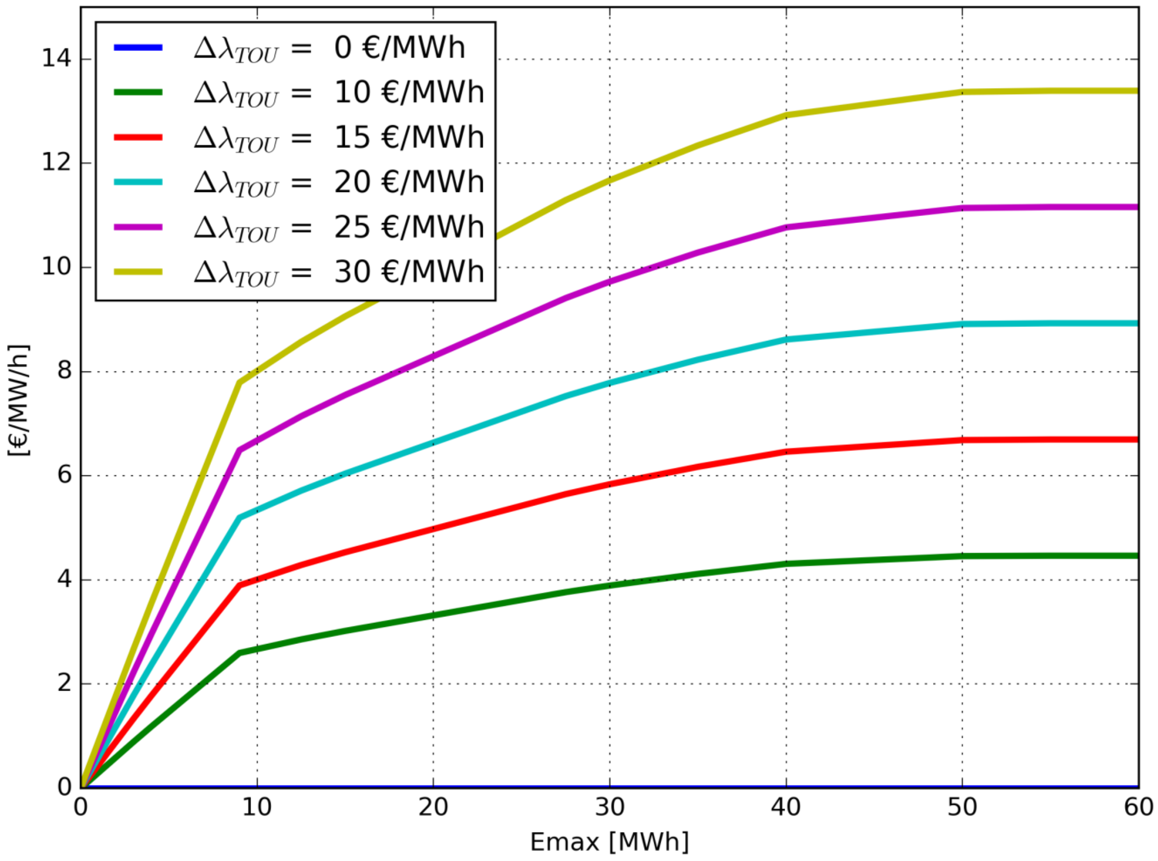


Figure 8 Scalability of the normalized business graph for ToU pricing as a function of changing $\Delta\lambda_{TOU}$ price difference.

A number of normalized business case graphs for ToU pricing with different $\Delta\lambda_{TOU}$ price differences are shown in Figure 8. The chosen price differences are $\Delta\lambda_{TOU}$ = 0 €/MWh (blue), $\Delta\lambda_{TOU}$ = 10 €/MWh (green), $\Delta\lambda_{TOU}$ = 15 €/MWh (red), $\Delta\lambda_{TOU}$ = 20 €/MWh (cyan), $\Delta\lambda_{TOU}$ = 25 €/MWh (purple), and $\Delta\lambda_{TOU}$ = 30 €/MWh (olive).

For no difference between low and high ToU tariff, $\Delta\lambda_{TOU}$ = 0 €/MWh, the price is constant, independently on the time of the consumption. As there are no price differences over time, there is also no added value of additional flexibility in the process. This is indicated in Figure 8 by a dark blue line that coincides with the x-axis of the graph. In the cyan color, the normalized business case graph for $\Delta\lambda_{TOU}$ = 20 €/MWh is shown, which is the same graph as previously shown in Figure 7. In green color, the normalized business case graph for $\Delta\lambda_{TOU}$ = 10 €/MWh is given. Already at the first sight, it can be observed that this green graph ($\Delta\lambda_{TOU}$ = 10 €/MWh) lays halfway the blue ($\Delta\lambda_{TOU}$ = 0 €/MWh) and cyan graph ($\Delta\lambda_{TOU}$ = 20 €/MWh).

Moreover, all the graphs for $\Delta\lambda_{TOU}$ = 10 €/MWh (green), $\Delta\lambda_{TOU}$ = 15 €/MWh (red), $\Delta\lambda_{TOU}$ = 20 €/MWh (cyan), $\Delta\lambda_{TOU}$ = 25 €/MWh (purple), and $\Delta\lambda_{TOU}$ = 30 €/MWh (olive) are equidistant.

A numerical comparison of the flexibility value for the battery sizes 9 and 60 MWh and for different $\Delta\lambda_{TOU}$ price differences is given in Table 1. The price difference $\Delta\lambda_{TOU}$ = 10 €/MWh is chosen to be the reference price difference, and we define a scaling factor as a quotient of the flexibility value for another $\Delta\lambda_{TOU}$ and the flexibility value for the reference price difference $\Delta\lambda_{TOU,ref}$ = 10€/MWh. The scaling factor is added to the table in a separate column next to the column in which the flexibility value is given. The line in which the reference price difference of $\Delta\lambda_{TOU,ref}$ = 10€/MWh is presented is highlighted in orange.

Table 1 Computed value of flexibility [€/MWh] for different $\Delta\lambda_{TOU}$ prices at the generic battery size of 9 MWh and 60 MWh, and the scaling factor

Battery size [MWh]	$\Delta\lambda_{TOU}$ [€/MWh]	Flex value [€/MW/h]	Scaling factor [-]	Battery size [MWh]	$\Delta\lambda_{TOU}$ [€/MWh]	Flex value [€/MW/h]	Scaling factor [-]
9	10	2,6	1	**60**	10	4,475	1
9	15	3,9	1,5	**60**	15	6,7	1,5
9	20	5,2	2	**60**	20	8,925	2
9	25	6,5	2,5	**60**	25	11,15	2,5
9	30	7,8	3	**60**	30	13,4	3

From Table 1, it can be observed that the scaling factor grows linearly with the increase in $\Delta\lambda_{TOU}$ price. Moreover, the scaling factor obtained as a quotient of the flexibility value and the reference flexibility value perfectly corresponds to the quotient of the price difference $\Delta\lambda_{TOU}$ and the reference ToU price difference $\Delta\lambda_{TOU,ref}$ in all the points of the normalized business case graph. For instance, for the battery size 9 MWh, the flexibility value for the reference price difference $\Delta\lambda_{TOU,ref}$ = 10 €/MWh is 2,6 €/MW/h. For the same battery size, and $\Delta\lambda_{TOU}$ = 25 €/MWh, the computed flex value is 6,5 €/MW/h, which is exactly

$$\Delta\lambda_{TOU,ref}/\ \Delta\lambda_{TOU} * 2{,}6\ €/MW/h = 2{,}5 * 2{,}6\ €/MW/h = 6{,}5\ €/MW/h$$

Hence, from a single normalized business case graph computed for a reference price difference $\Delta\lambda_{TOU,ref}$, it is possible to find the normalized business case graph for any $\Delta\lambda_{TOU}$ (as long as the shape of this graph is the same as the shape of the reference graph, i.e., as long as the low tariff periods are equally long). In conclusion, it is sufficient to compute a single business case graph for e.g. $\Delta\lambda_{TOU}$ = 10 €/MWh. This graph scales perfectly linearly as a function of $\Delta\lambda_{TOU}$ price difference as explained above.

3.3.2 Business case graph with peak pricing

So far, only the case with ToU electricity ***energy*** price was considered, whereas the peak component was set to 0 ($\Delta\lambda_{TOU} \geq 0$ €/MWh, $\lambda_C = 0$ €/MW). In this section, we show the consequences on the value of flexibility of additional pricing for the highest (peak) consumption. Additionally, the scalability of the normalized business case graphs with additional peak pricing component λ_C is discussed.

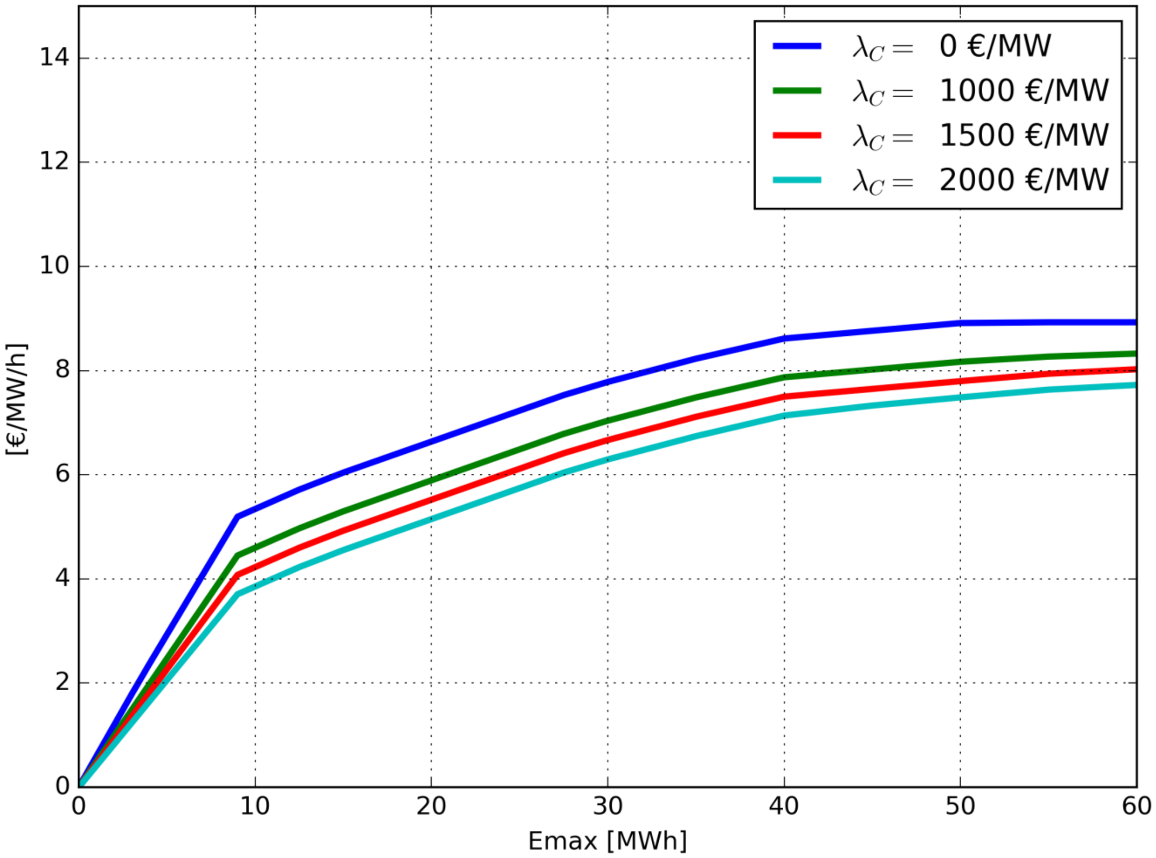


Figure 9 Dependence of the normalized business case graph for ToU pricing on the peak price component variations. The ToU price difference $\Delta\lambda_{TOU}$ is fixed to 20 €/MWh.

Figure 9 shows the normalized business case graph for ToU pricing with the ToU price difference $\Delta\lambda_{TOU}$ fixed to 20 €/MWh, and with the peak price λ_C varying from 0 €/MW to 1000 €/MW to 1500 €/MW to 2000 €/MW.

The peak price values in this illustrative example are chosen to be related to the network tariffs, which charge the maximum power consumption over a certain predefined period in time. The peak prices in range from 0.95 €/kW/month to 1.95 €/kW/month can be considered realistic for electricity consumers in Belgium at the time of writing for connections to the middle and high voltage level electricity grid, although it should be noted that these values are evolving over time (as it is the case with tariff structures and prices in general).

Several conclusions can be drawn from the presented figure.

First, it can be observed that with the increase in the peak price, the normalized flexibility value in €/MW/h decreases. This decrease is not negligible even for the lowest realistic network tariff, i.e. peak price λ_C = 1000 €/MW. Due to the introduction of peak tariff of λ_C = 1000 €/MW in the ToU pricing regime with the ToU price difference of $\Delta\lambda_{TOU}$ = 20 €/MWh, the flexibility value decreased for approximately 15%. The introduction of a peak price of λ_C = 2000 €/MW led to a drop in flexibility value of roughly 30%. Therefore, due to the large impact on the flexibility value, the network charges should not be excluded from consideration in this business case.

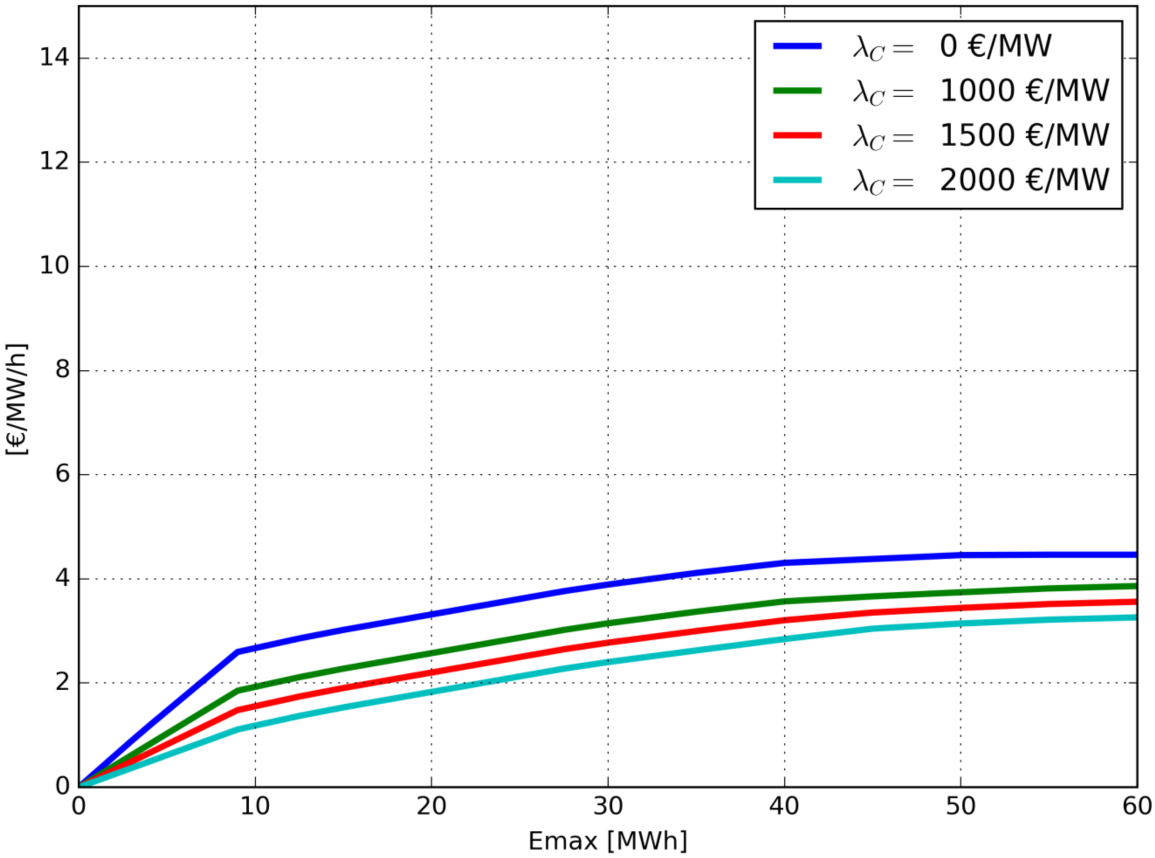


Figure 10 Dependence of the normalized business case graph for ToU pricing on the peak price component variations. The ToU price difference $\Delta\lambda_{TOU}$ is fixed to 10 €/MWh.

Second, it can be observed that with the addition of the network tariff (peak price) λ_C, the property of linear scalability of the normalized business case graphs remained intact. Figure 10 and Figure 11 show that for other ToU price difference $\Delta\lambda_{TOU}$, namely $\Delta\lambda_{TOU}$ = 10 €/MWh and $\Delta\lambda_{TOU}$ = 30 €/MWh, respectively, the scalability property is maintained. The data presented visually in Figure 11 is given in table format in Table 2.

It is important to keep in mind, however, that in nearly all practical situations, the peak price is not caused by the peak of the flexible part of the process only, but caused by the peak of the overall plant consumption. In most industrial plants only a part of the industrial activities has flexibility and the non-flexible parts will contribute to the peak as well. The results in this section have been achieved assuming that the non-flexible part of the process has constant power consumption. The scaling properties have not been investigated in case the non-flexible power profile deviates from that constant power.

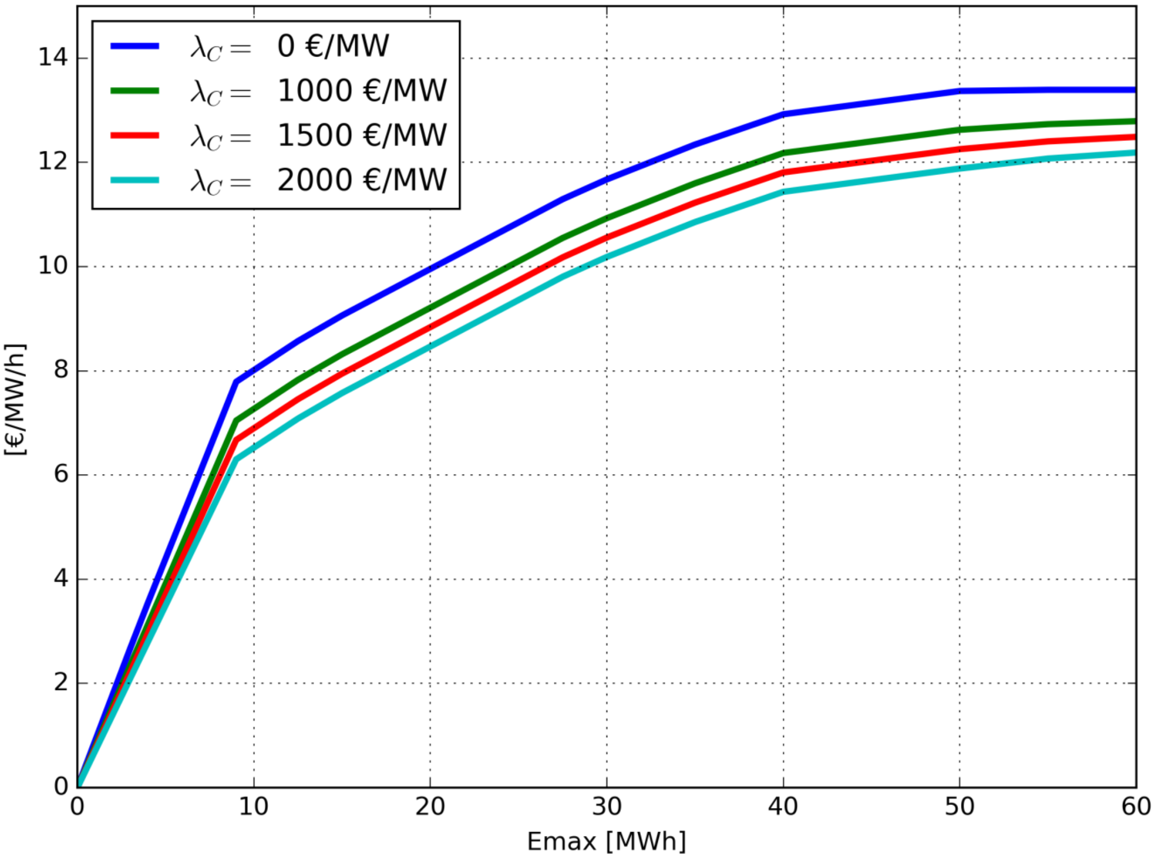


Figure 11 Dependence of the normalized business case graph for ToU pricing on the peak price component variations. The ToU price difference $\Delta\lambda_{TOU}$ is fixed to 30 €/MWh.

Table 2 Data given in Figure 11 in table format. Flexibility value [€/MW/h] in dependence on the peak price component variations for fixed $\Delta\lambda_{TOU}$ *= 30 €/MWh.*

Battery Size [MW]	λ_C = 0 €/MW	λ_C = 1000 €/MW	λ_C = 1500 €/MW	λ_C = 2000 €/MW
0,1	0,36	0,31	0,30	0,28
0,2	0,71	0,63	0,59	0,56
0,5	1,79	1,57	1,48	1,40
1	3,57	3,13	2,97	2,80
2	7,14	6,26	5,93	5,60
5	17,59	15,66	14,83	14,00
10	32,05	29,08	27,59	26,10
20	39,82	36,85	35,36	33,87
30	46,70	43,72	42,23	40,74
40	51,70	48,72	47,23	45,74
50	53,48	50,51	49,02	47,53
60	53,57	51,16	49,96	48,76

3.4 Day-ahead market business case graph

3.4.1 Symmetrical battery business case

Graph calculation

The day-ahead business case graph in this section is generated with the following settings and data:

- Price profile (PP) optimization method with the Belgian Belpex day-ahead market price information from the 1st of January till 31st of March 2015. No peak price has been used.
- Generic battery reference model with the following settings:
    - Pin_max = 1 MW
    - Pout_max = 1 MW
    - Emax = 0.1 … 100 MWh

This case is called the “symmetrical” battery business case because the maximum charging (Pin_max) and discharging power (Pout_max) are equal.

Graph discussion

The normalized day-ahead business case graph for the symmetrical use of the generic battery reference model is shown in Figure 12. The graph is very steep, but non-linear, in the beginning and rises from 0 to more than 7 €/MW/h at 10 MWh battery size. From 10 MWh onwards the graphs starts saturating to a level around 9 €/MW/h. Especially for small battery sizes, the graph is difficult to read and a logarithmic scale works better. This is shown in Figure 13.

The profit starts saturating around a battery size of 8-10MWh which is explained by the typical and repetitive price profile of the day-ahead price. Figure 14 shows the average Belpex price over the first 3 months of 2015 as a function of the time of the day. On average, electricity is the cheapest between midnight and 6:00h. As from 6:00h on, the price starts increasing and peaks the first time around 9:00h. After lunch time the price profile shows a small dip again before it increases to its maximum around 18:00-19:00h. The predictability of this shape might change in the future when VRE in the power system increases.

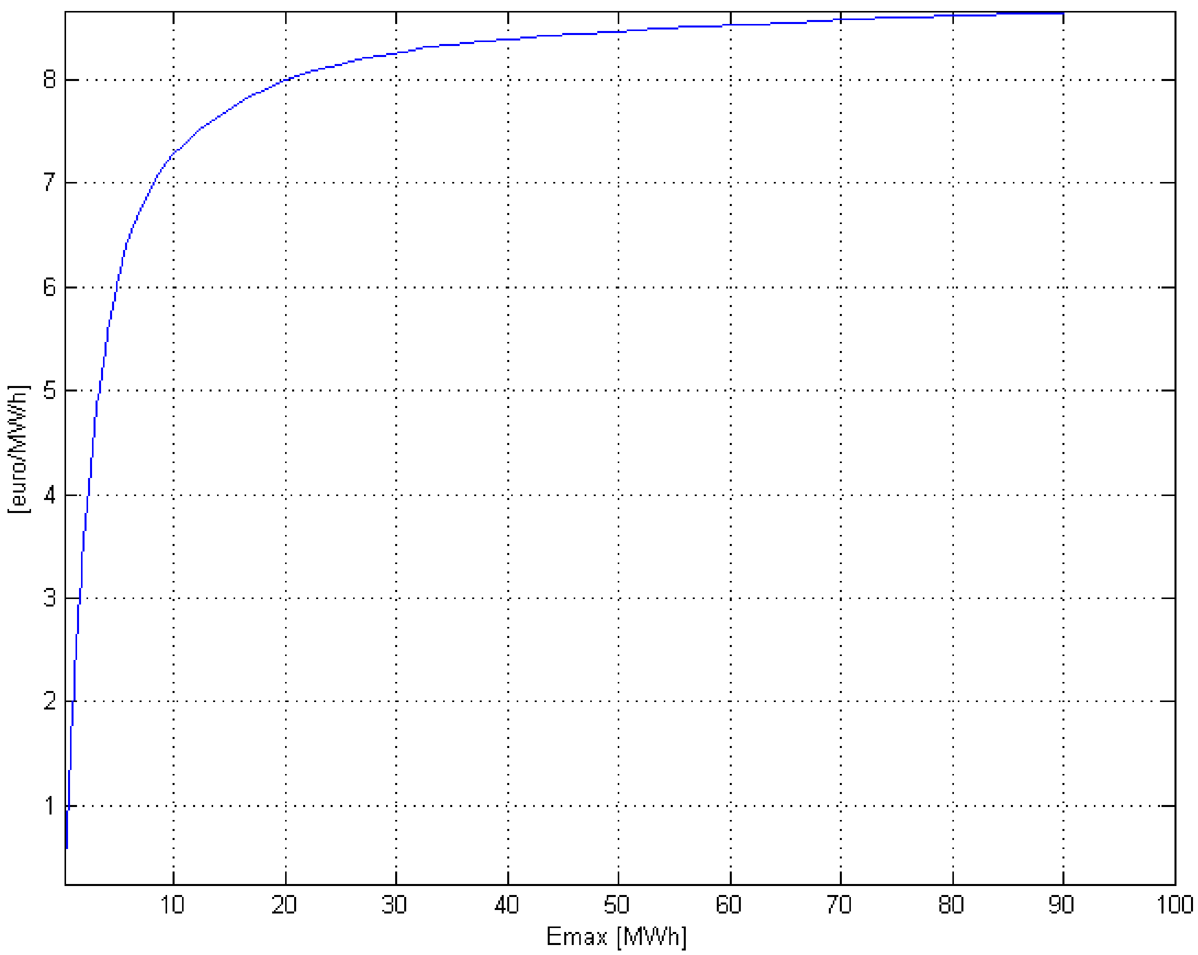


Figure 12: Normalized day-ahead business case graph for the generic battery reference model. The graph expresses the normalized business case profit (y-axis) as function of a varying battery size (x-axis) with fixed settings for Pin_max = Pout_max = 1 MW.

This results in a typical charging and discharging probability which is shown in Figure 14 as well. For example at 9:00h, the day-ahead price is quite high: During the optimization, only in 8% of the days it is profitable to charge at that moment in time while it is profitable to discharge the battery in 85% of the days. The “bulk” of the profit can be made by charging the battery during the cheap night prices and discharging during the expensive day time and a battery size of 8-10MWh is sufficient to do so.

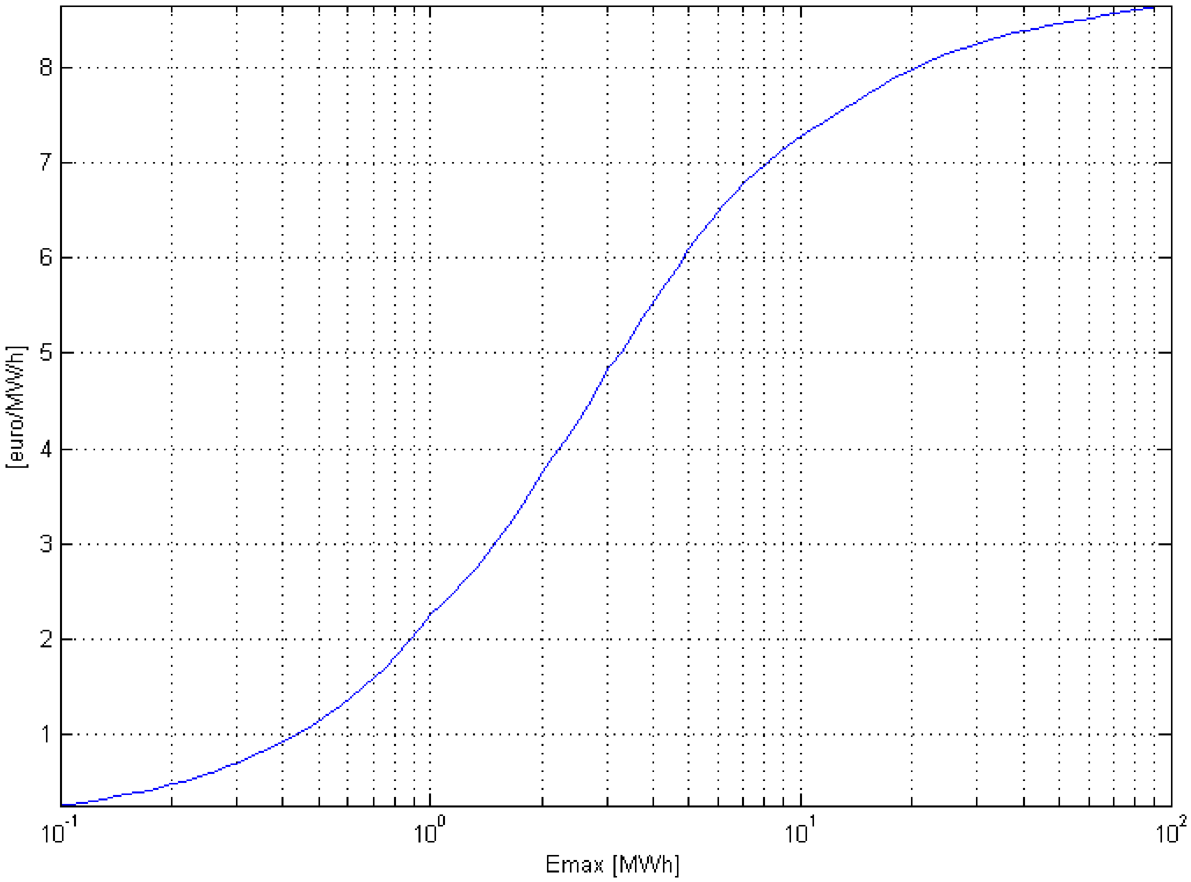


Figure 13: Normalized day-ahead business case graph for the generic battery reference model with a logarithmic scale on the x-axis.

Graph scaling properties

For the graphs in Figure 12 and Figure 13, the same Pin_max graph scaling rules as explained at the end of section 3.3.1 can be used.

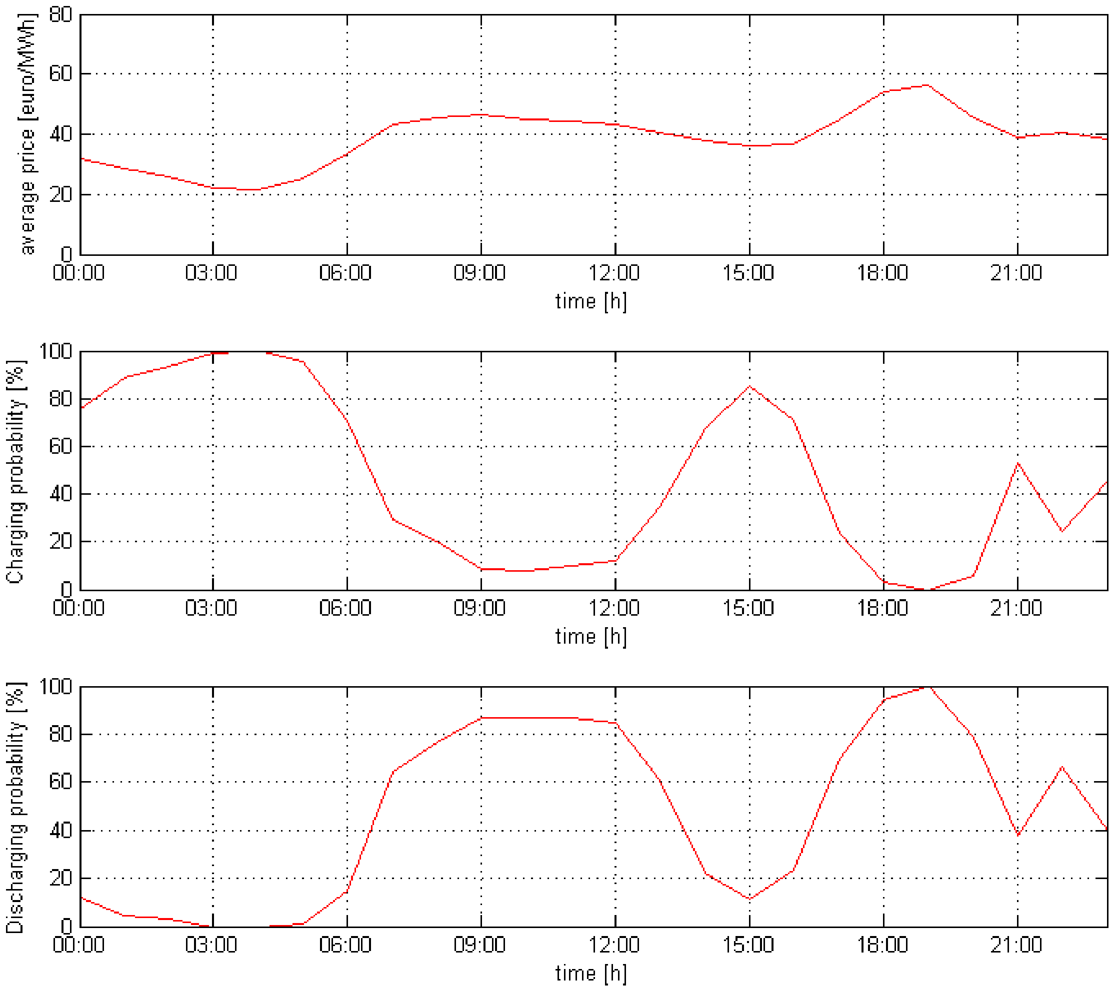


Figure 14: The average Belpex day-ahead price as function of the time of the day (upper), the charging probability (middle) and the discharging probability (lower).

3.4.2 Asymmetrical battery business case

The graph in the previous section is only valid in case when Pin_max is the same as Pout_max. For a battery this is quite a reasonable assumption, but for other processes which can be mapped on the generic battery reference model it is quite common that Pout_max is different from Pin_max. (see example in section 2.2.2).

Graph calculation

The day-ahead business case graph in this section is generated with the following settings and data:

- Price profile (PP) optimization method with the Belgian Belpex day-ahead market price information from the 1st of January till 31st of March 2015. No peak price has been used.
- Generic battery reference model with the following settings:
    - Pin_max = 1 MW
    - Pout_max = 0.1 … 20 MW logarithmically spaced
    - Emax = 0.1 … 100MW

Graph discussion

The normalized day-ahead business case graph for the asymmetrical use of the generic battery reference model is shown in Figure 15. The graph contains several lines for different values of Pout_max. The line with label 1 MW is the case where the battery is used symmetrical and is the same as the graph in Figure 13.

For other values of Pout_max, the shape of the graphs remains more or less the same. For low battery sizes the business case value is quite independent of Pout_max. Especially for battery sizes smaller than 1MWh, not a lot of profit can be made of a large output power. This is explained by the fact that the day-ahead market is hourly based and whether the battery is emptied in 10 minutes or an hour makes no difference in the price. For large battery sizes, however, the advantages of large output power are clearly visible in the right half of Figure 15.

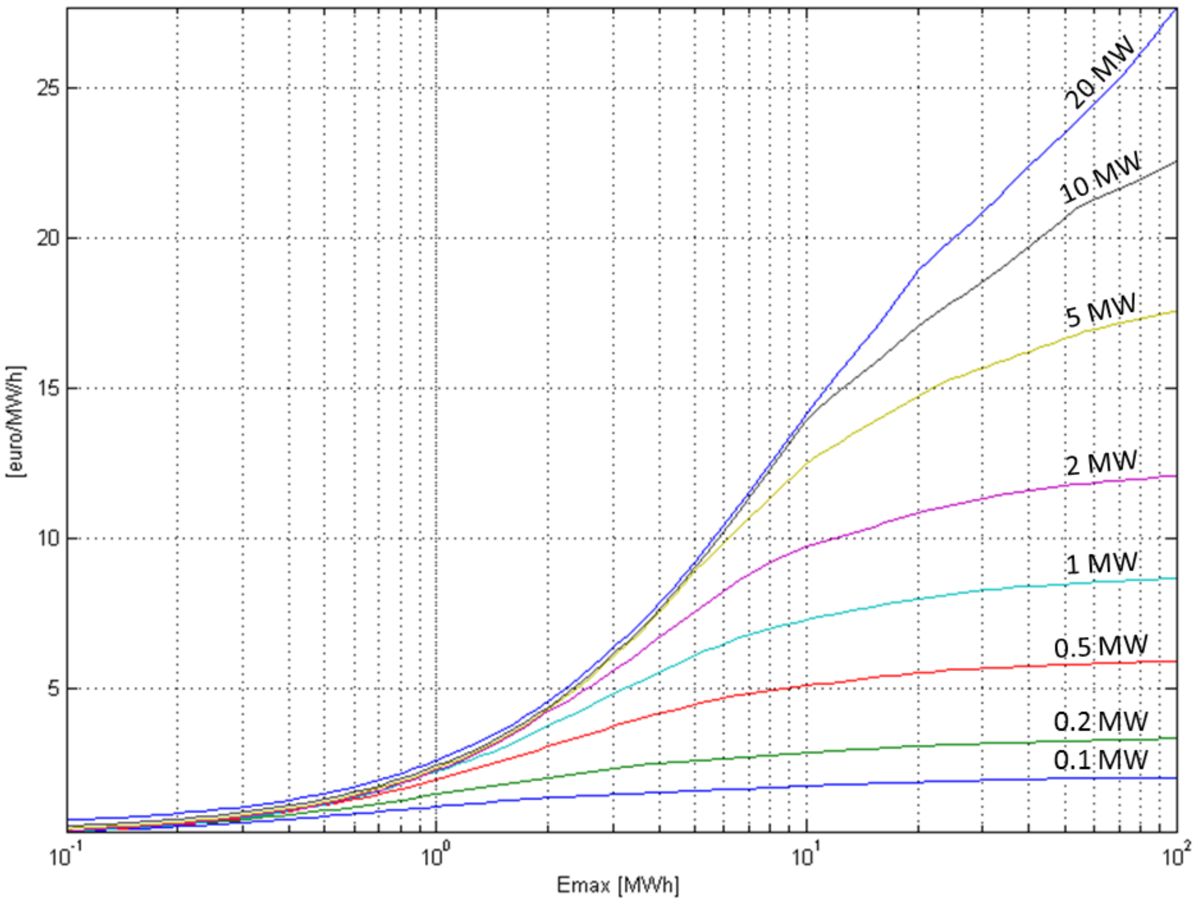


Figure 15: Normalized day-ahead business case graph for the generic battery reference model. The graph expresses the normalized business case profit (y-axis) as a function of a varying battery size (x-axis). The calculation is performed for different values of Pout_max (0.1 … 20MW).

Graph scaling properties

The graph scaling still works more or less the same way as in the previous sections, but Pout_max has to be normalized as well. The actual business case value is still calculated as:

- Value = Value_norm . Pin_max

Value_norm is the normalized business case value found in the graph at Emax_norm on the plot with label Pout_max_norm, with:

- Emax_norm = Emax / Pin_max
- Pout_max_norm = Pout_max / Pin_max

Numerical example: suppose a battery with size of 16 MWh and a maximum charging power of 0.8 MW and a maximum discharging power of 4 MW:

- Emax_norm = 16 / 0.8 = 20
- Pout_max_norm = 4 / 0.8 = 5
- Value_norm = 14.8 €/MW/h (see Figure 15 on 5 MW line)
- Value = 14.8 x 0.8 = 11.84 €/h

3.5 Imbalance market business case graph

In this section, the reference battery model of the following parameters is considered

- Pin_max = 1 MW
- Pout_max = 1 MW
- n = 1
- Emax = variable, 0.1 – 50 MWh.

The reference battery model is hence symmetric (Pin_max = Pout_max). The utilized prices are realized historic imbalance prices in Belgium in the period from 1 January 2015 until 31 March 2015. The dual imbalance price method as explained in [3] is utilized to compute the normalized business case graph shown in Figure 16.

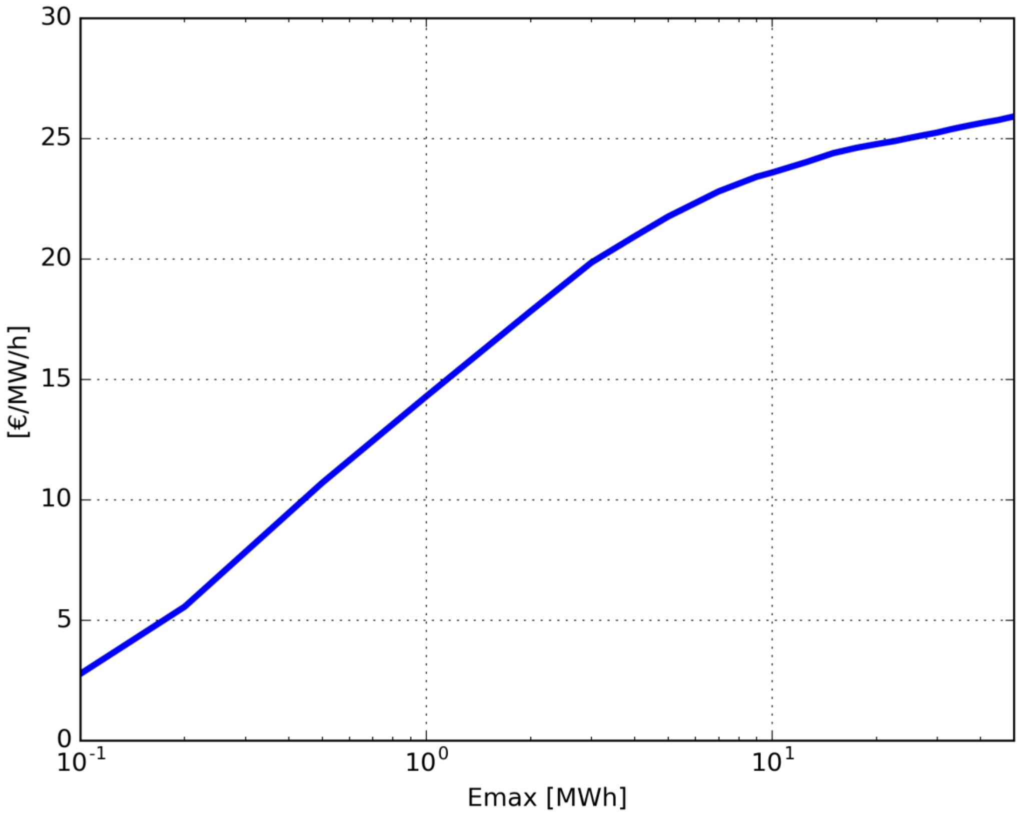


Figure 16: Normalized business case graph for the generic battery reference model for the imbalance use case. The graph expresses the normalized business case profit (y-axis) as a function of a varying battery size (x-axis, logarithmic scale).

A steep increase in flexibility value for the generic battery sizes in the interval 0.1 MWh,..., 8 MWh is observed in Figure 16. In this interval, the value grows from 2.5 €/MW/h to 22.5

€/MW/h. Similar steep growth in flexibility value was already observed for the day-ahead market business case in Figure 12 (in linear scale) and Figure 13 (in logarithmic scale).

Beyond the battery size of 8 MWh, the flexibility value keeps on increasing with the increase in the flexibility size. However, this growth is less steep compared to the initial one. In the interval of the generic battery size from 8 MWh until 50 MWh, the flexibility value increased “only” from 22.5 €/MW/h to 26 €/MW/h. Similarly as for the day-ahead market business case, the fast growth of profit (i.e. flexibility value) for smaller generic battery sizes, and slower growth for larger generic battery size is explained by the properties of the imbalance prices.

For the graph in Figure 16, the same Pin_max graph scaling rules as explained at the end of section 3.3.1 can be applied.

As discussed earlier in [3], both the normalized business case graph for the generic battery reference model for the day-ahead and imbalance use case are obtained under the underlying assumption of perfect price forecast. Therefore, they should be interpreted as the upper bound on the flexibility value, which can and will be lower in practice due to imperfect price forecasts. In practice, this also means that the reliability and correctness of price forecasts will determine to what extent this potential value can be valorized in practice. The complexity and uncertainty of these forecasts, together with the risk management strategy of a company with flexible industrial demand will determine the attractiveness of one or another possible business case. Moreover, the flexibility value is obtained from historical data, and long term trends in market clearing price development are not taken into account. Therefore, this methodology is more suitable for shorter term (operational) business models of a year up to several years, and less suitable for long term business models of more than 5 years. Additionally, sudden changes in market and/or regulatory frameworks that impact the price evolutions and more specifically price dynamics in those markets, could immediately impact the business case assessment results

3.6 On-site VRE business case graph

Reference model configuration

This section will discuss the configuration where a renewable energy source is connected on-site to an industrial customer. Figure 17 shows the interconnections between the renewable energy resource, industrial customer and the grid. In the left figure, the industrial customer needs more electricity than the wind turbine produces and electricity is bought from the grid. In the right figure, the wind turbine produces more electricity than the industrial customer needs and the excess electricity is injected in the grid.

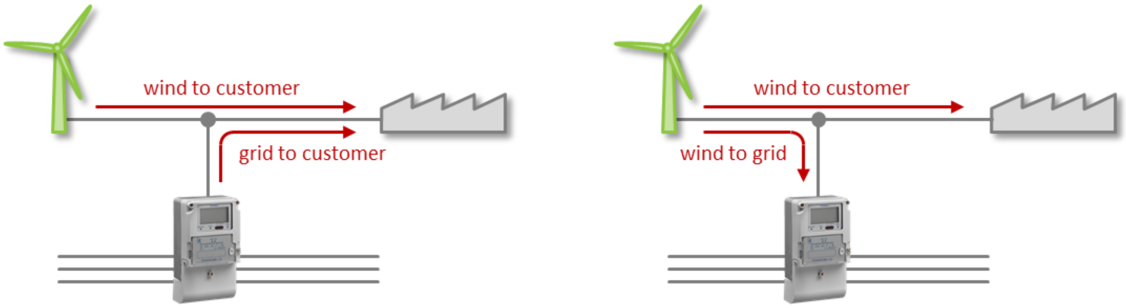


Figure 17: On-site VRE interconnections between the renewable energy source, industrial customer with flexibility and the grid. The left figure shows the energy flows in case the industrial customer consumes more electricity than the wind turbine produces, the right figure shows the energy flows in case of excess wind production.

On-site VRE can result in an interesting business case under the condition that electricity from the wind turbine can be bought at a lower price than electricity from the grid. The present flexibility can be used to buy extra electricity from the wind turbine when excess renewable energy is available which reduces buying expensive electricity from the grid.

In order to create a normalized reference graph for a generic battery model, it is important to introduce an additional inflexible load. In case only a battery would be used, there would not be a need to buy expensive electricity from the grid which is a fundamental part of the business case. Figure 18 shows the configuration which has been used for the generation of normalized on-site VRE business case graphs. It is assumed that industrial process consists of a generic battery and a fixed inflexible load. When excess wind energy is available, the battery will be charged. When there is not a lot of wind energy, the battery will be discharged.

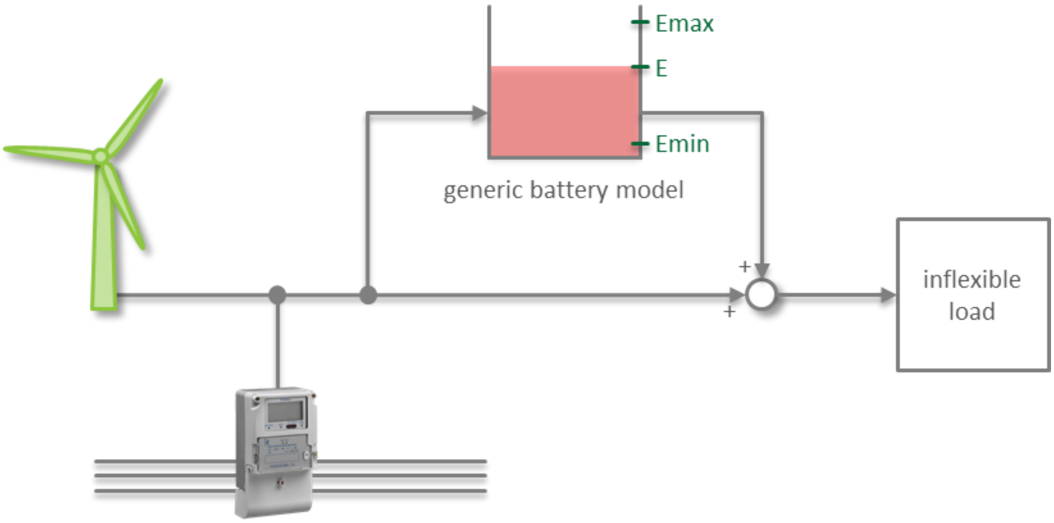


Figure 18: The use of a generic battery model in combination with an inflexible load for the generation of normalized business case graphs.

Example optimization

In this section it is explained how a single point of a business case graph is constructed. The example is generated with the following settings and data:

- A realistic wind profile for 1 day, scaled to the production of a 1MW wind turbine. A day is selected where the wind production is sometimes higher, sometimes lower than the fixed, inflexible load.
- Generic battery reference model with the following settings:
  - Pin_max = 1 MW
  - Pout_max = 1 MW
  - Emax = 1 MWh
- A fixed inflexible load of 0.5MW
- Price setting:
  - Buy electricity from the wind turbine: 40 €/MWh
  - Resell electricity from the wind turbine to the grid: 36 €/MWh
  - Buy electricity from the grid: 100 €/MWh

With the above settings, 2 simulations are executed: a reference simulation and a simulation where the battery is used in an optimal was. The simulation results are shown in Figure 19 and Figure 20.

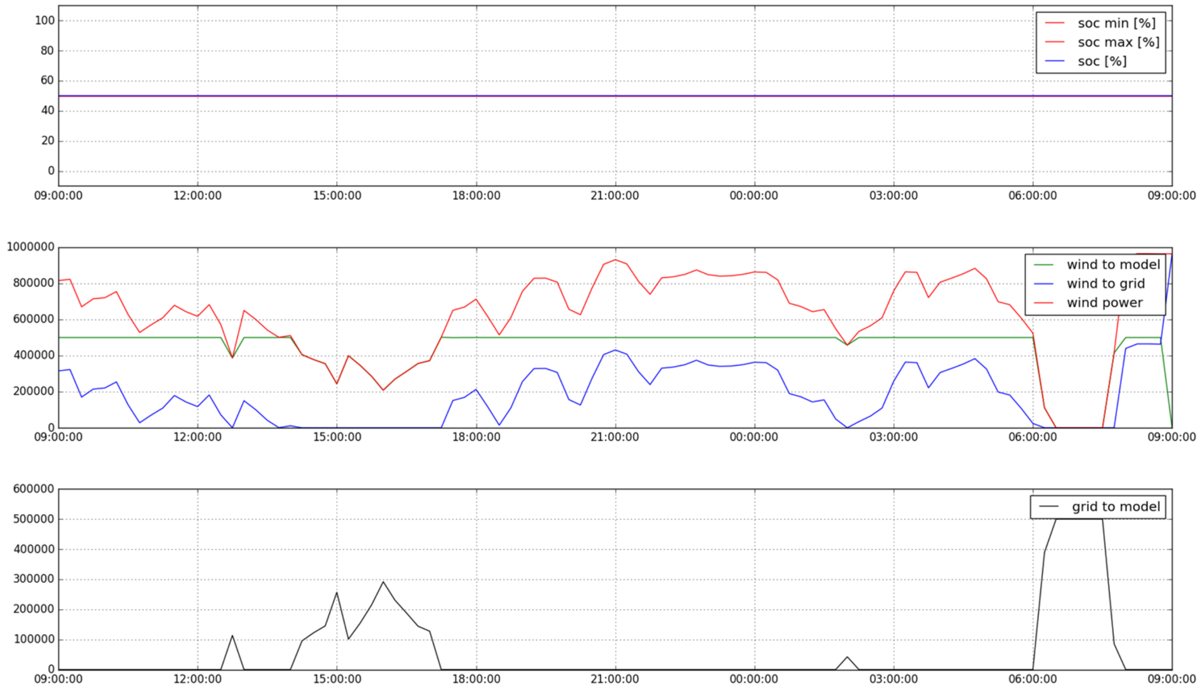


Figure 19: Reference case calculation.

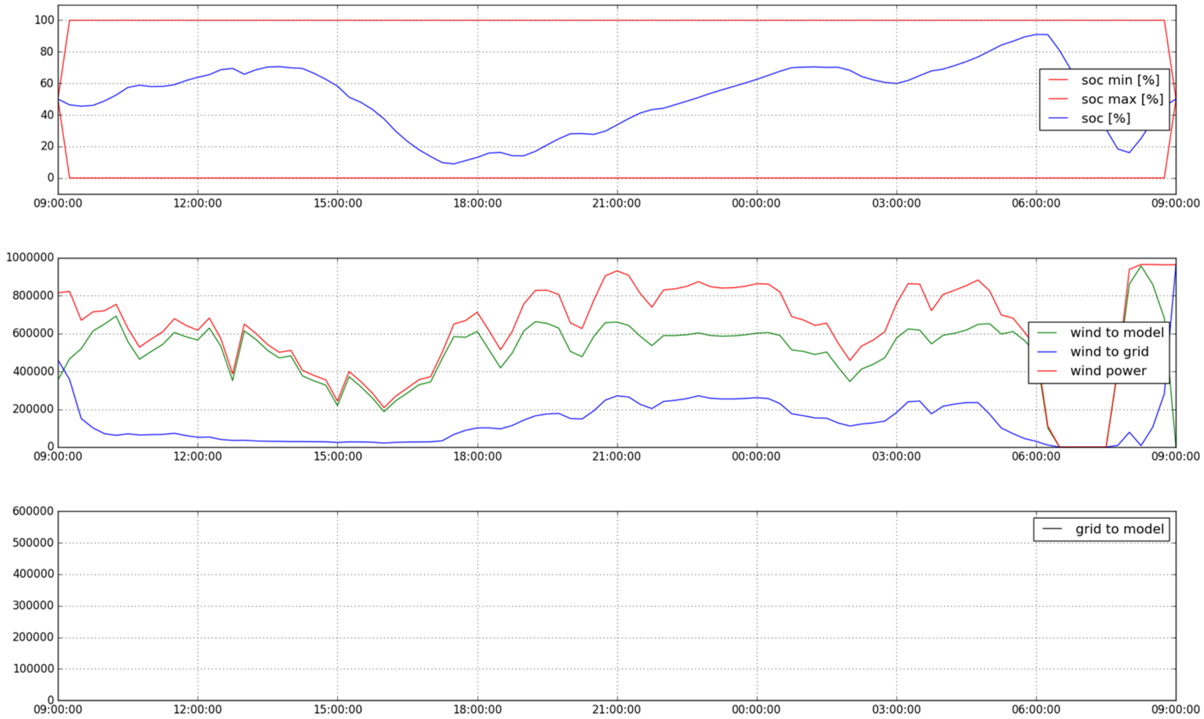


Figure 20: Optimal use of the battery model.

During the reference case simulation, the battery (flexibility) is not used. In the upper plot of Figure 19 is clearly seen that the state of charge of the battery stays at 50% during the whole simulation. In the middle plot the wind production is shown (red): All electricity up to 0.5MW is used by the reference model (green) and the excess electricity (blue) is injected in the grid. At some moments in time, the wind turbine generates not enough electricity and electricity has to be bought from the grid. This is shown in the lower plot (black).

Energy balance summary reference simulation:

- Total wind production: 15.23 MWh
- Wind energy injected in the grid: 4.53 MWh
- Wind energy used by the reference model: 10.70MWh
- Electricity bought from the grid: 1.3MWh

Total cost summary reference simulation:

- Buying electricity from the wind turbine costs 15.23 x 40 = 609.20€
- Reselling excess electricity to the grid gets 4.53 x 36 = 163.08€
- Buying electricity from the grid costs 1.3 x 100 = 130€
- Total cost: 609.20€ – 163.08€ + 130€ = 576.12€

During the optimization, the battery is used in an optimal way. In the upper plot of Figure 20 is seen that the battery is charged when there is more wind than inflexible load can consume. At moments of low wind the battery is discharged. It is seen in the middle plot that the amount of injected electricity in the grid is reduced (blue) and no electricity has to be bought from the grid anymore (black line in the lower plot)

Energy balance summary during optimization:

- Total wind production: 15.23 MWh
- Wind energy injected in the grid: 3.23 MWh
- Wind energy used by the reference model: 12 MWh
- Electricity bought from the grid: 0 MWh

Total cost summary reference simulation:

- Buying electricity from the wind turbine costs 15.23 x 40 = 609.20€
- Reselling excess electricity to the grid gets 3.23 x 36 = 116.28€
- Buying electricity from the grid costs 0€
- Total cost: 609.20€ – 116.28€ = 492.92€

Optimal use of the flexibility in the battery results in a cost reduction of 83.20€ over 24h or on average 3.47€/h.

Graph calculation

The business case graph in this section is generated with the following settings and data:

- Actual measured wind profile measured from 1st of January till 31st of March 2011 and scaled to a wind turbine power of 1MW.
- Generic battery reference model with the following settings:
    - Pin_max = 1 MW
    - Pout_max = 1 MW
    - Emax = 0.1 … 100MW
    - Fixed inflexible load = 0.1 … 1MW
- Price setting:
    - Buy electricity from the wind turbine: 40 €/MWh
    - Resell electricity from the wind turbine to the grid: 40 €/MWh
    - Buy electricity from the grid: 100 €/MWh

Graph discussion

The normalized on-site VRE business case graph for a generic battery reference model in combination with a fixed inflexible load is shown in Figure 21. The graph contains several lines for different values of the fixed inflexible load. The major trend is similar to other business cases: the business case value increases with the battery size and especially for low fixed inflexible loads there comes a point where increasing the battery size doesn't make sense anymore.

Further it is seen that increasing the fixed inflexible load in first instance results in a better business case but above a certain value, the business case value drops again. This is better visualized in Figure 22, where the same data is represented in a different way: the fixed inflexible load is plotted on the x-axis for different battery sizes. The plots in Figure 22 clearly show that the business case value is very small and going to zero for very small and very high fixed inflexible loads with a maximum in the range between 0.2MW and 0.3MW. The peak is more explicit for large battery sizes compared to small battery sizes.

The observation that the business case is zero when the fixed load is very high is easy to explain: when the fixed load is higher than the maximum capacity of the wind turbine, the renewable energy can be consumed by the fixed load under all conditions.

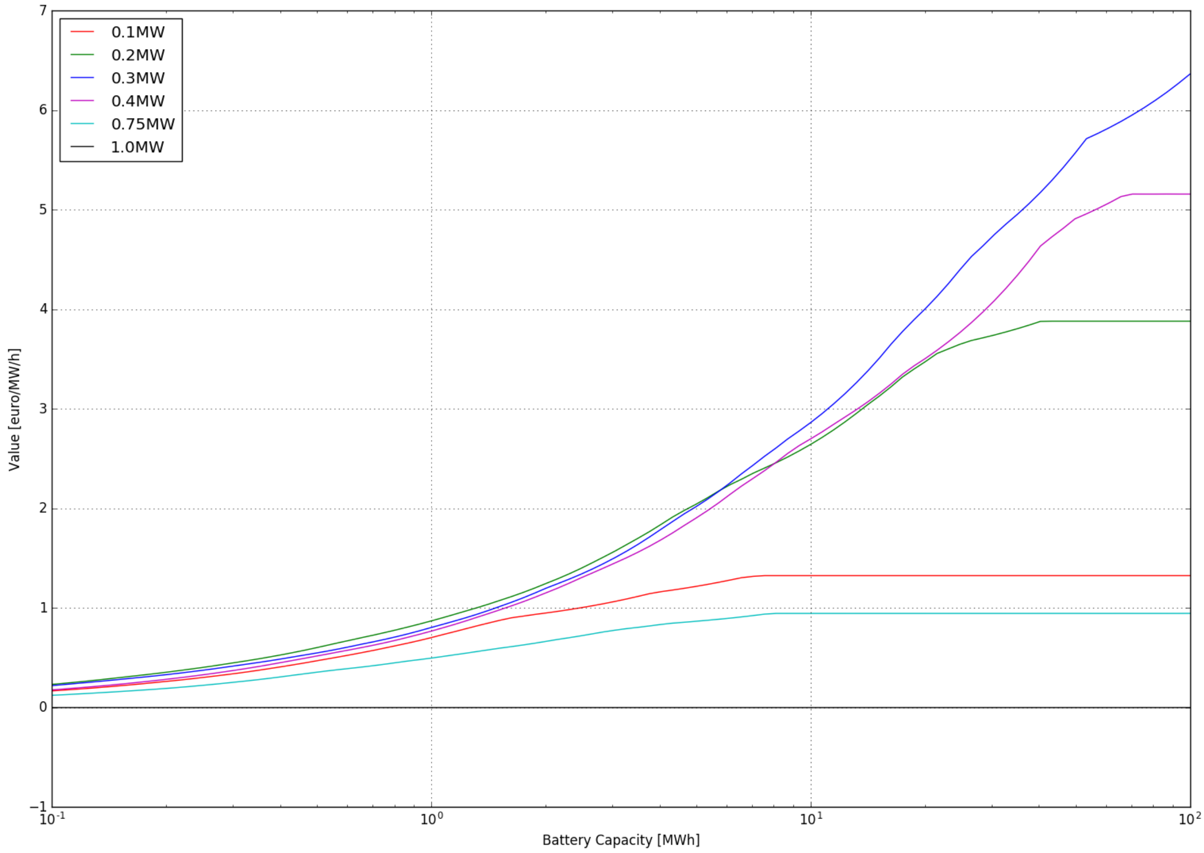


Figure 21: Normalized on-site VRE business case graph for the generic battery reference mode in combination with a fixed load. The graph expresses the normalized business case profit (y-axis) as a function of a varying battery size (x-axis). The calculation is performed for different values of the fixed inflexible load (0.1 … 1MW).

Further, it is quite intuitive to understand that a battery is used optimal under the condition that there are lots of charging and discharging opportunities. For very low fixed inflexible load values, the probability that the wind production is higher than the fixed load is high and the number of opportunities to discharge become smaller.

In practice, the fixed inflexible load can be interpreted as a simplified representation of an industrial customers' electricity consumption. Although it is a simplification, Figure 22 shows that an optimal on-site VRE business case requires a good match between the installed VRE capacity and the year consumption of the plant.

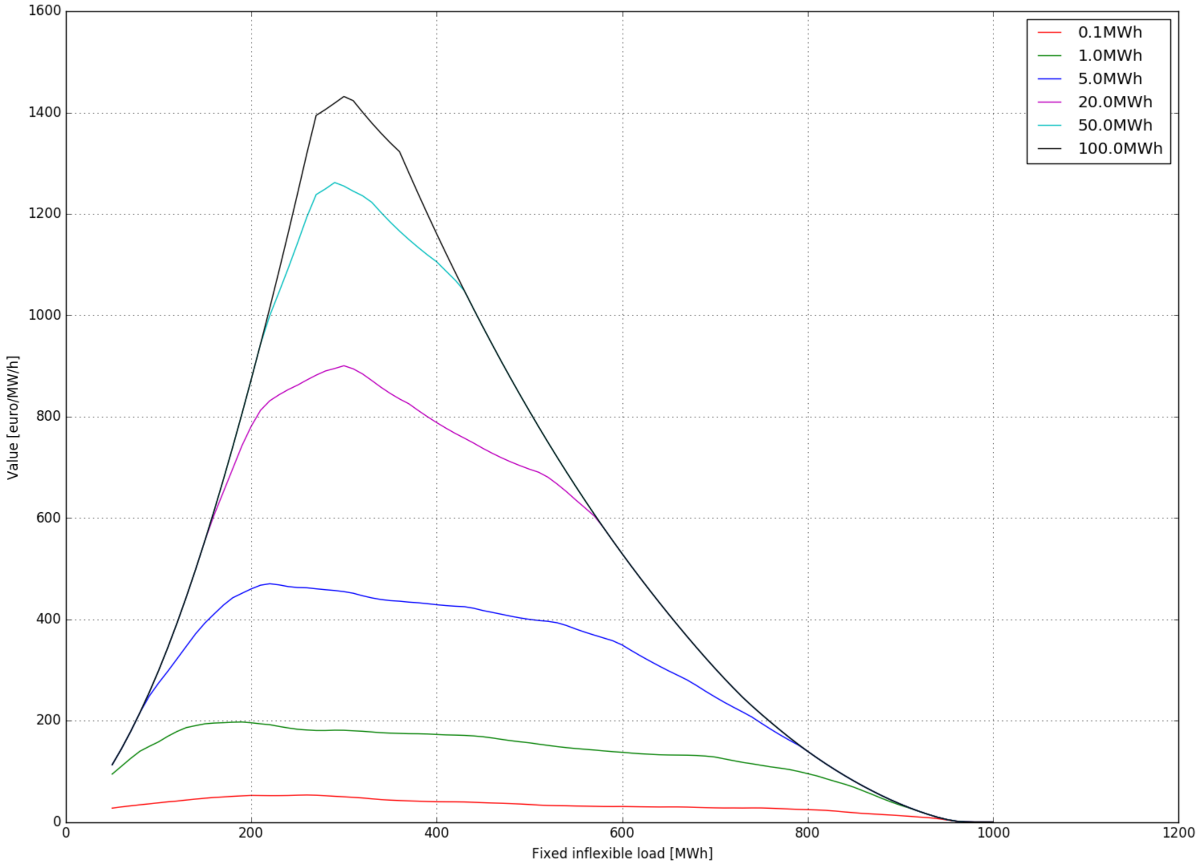


Figure 22: The same data as in Figure 21, but in this graph the normalized business case profit (y-axis) is expressed as a function of the fixed inflexible load (x-axis) for different battery size values (0.1 … 100MWh).

Graph scaling property 1: price difference scaling

The graphs in Figure 21 and Figure 22 are generated for the following price setting:

- Buy electricity from the wind turbine: 40 €/MWh
- Resell electricity from the wind turbine to the grid: 40 €/MWh
- Buy electricity from the grid: 100 €/MWh

The wind turbine buy and sell price are set equal to eliminate an additional degree of freedom. This approximation is justified by the fact that the price difference between buying and selling is relatively small and a good business case limits the amount of electricity which should be sold to the grid anyway. By doing so, the graphs in Figure 21 and Figure 22 scale with the price difference between the grid buy price and the wind turbine buy price.

Numerical example: suppose a battery with size of 10 MWh and a fixed inflexible load of 0.4MW. Buying electricity from the wind turbine costs 38.66 €/MWh and buying electricity from the electricity grid costs 109.53 €/MWh or a price difference of 70.87€/MWh.

The business case value for a battery size 10MWh and an inflexible load of 0.4MW is 2.70 €/MW/h (see Figure 21). That graph is generated for a price difference of 60€/MWh and consequently the business case value for a price difference of 70.87€/MWh is scaled linearly: Value = 2.70 / 60 x 70.87 = 3.19 €/MW/h.

Graph scaling property 2: Pin_max scaling

The Pin_max scaling property, as explained in previous sections (e.g. 3.3.1), remains valid for the on-site VRE business case, but additional scaling on the wind turbine power and the fixed inflexible load is required:

.The actual business case value is still calculated as:

- Value = Value_norm . Pin_max

Value_norm is the normalized business case value found in the graph at Emax_norm on the plot with:

- Emax_norm = Emax / Pin_max
- P_fixed_inflexibile_load_norm = P_fixed_inflexibile_load / Pin_max
- P_wind_turbine_norm = P_wind_turbine / Pin_max
- Value = Value_norm x Pin_max

Numerical example: suppose a battery with size of 15 MWh and a maximum charging power of 2.3 MW, a wind turbine of 2.3 MW and a fixed load of 0.8MW:

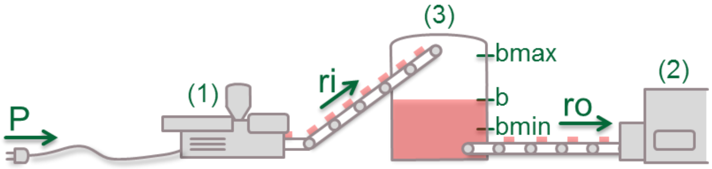
- Emax_norm = 15 / 2.3 = 6.52 MWh
- P_fixed_inflexibile_load_norm = 0.8/2.3 = 0.347MW
- Value_norm = 2.3 €/MW/h (see Figure 1)
- Value = 2.3 x 2.3 = 5.29 €/h

As seen in the above equations, the wind turbine power has to scale together with Pin_max for the graphs in Figure 21 and Figure 22. In principle this is an additional degree of freedom which is important, but not explored in this deliverable.

3.7 Practical example

Description of the process

In this section, the same example of section 2.2.2 will be used to demonstrate the use of normalized business case graphs.



The example consists of a polypropylene pelletizer production line with a pelletizer which can be modulated between 30 and 100%. The pelletizer has a maximum production capacity of 20 ton/h and has an electricity consumption of 200 kWh/ton. At the maximum production level, the pelletizer consumes 4 MW. The polypropylene pellets are stored in a bulk storage silo with a maximum capacity of 500 ton. For production security reasons the minimum capacity in the storage silo should not be lower than 100 ton. The buffer feeds the rest of the production process and has a constant feed of 14 ton/h.

- ro = 14.000 kg/h
- K = 5 kg/kWh
- bmin = 100.000 kg
- bmax = 500.000 kg
- Pmin = 1.200 kW

In the next steps it is explained, how the business case value can be achieved by means of the simplified calculation methodology.

Step 1: mapping on the generic reference model

As explained in section 2.2.2, the above process can be mapped on the generic battery model with the following parameters:

- Emax = 80 MWh
- Pin_max = 1.2 MW
- Pout_max = 1.6 MW

Step 2: normalizing the parameters of the reference model

As explained in section in section 3.2, the parameters have to be normalized in order to use the normalized business case graphs. Normalization is done by dividing all parameters by Pin_max resulting in the following normalized parameters:

- Emax_norm = 66.7 MWh
- Pin_max_norm = 1 MW
- Pout_max_norm = 1.33 MW

Step 3: find the normalized business case value in the graph

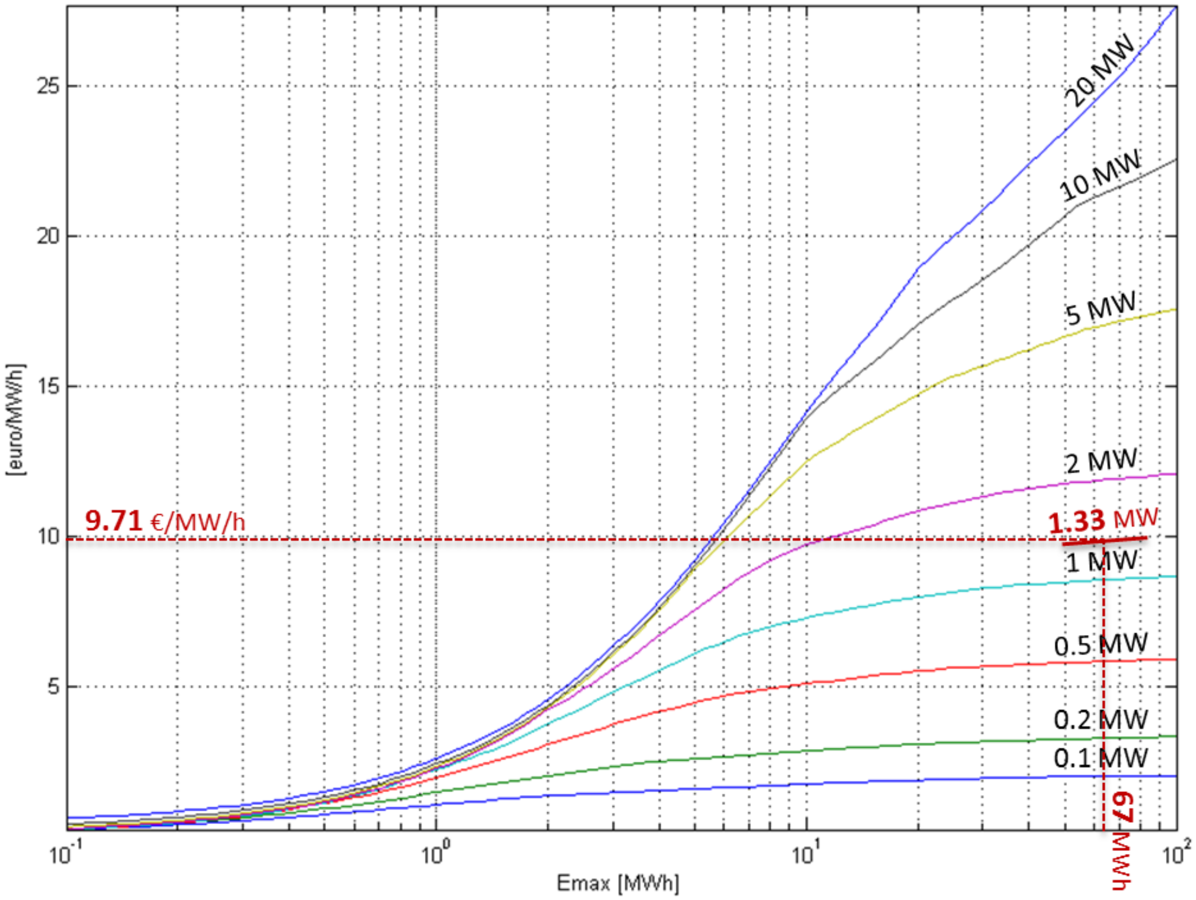


Figure 23: Looking up the normalized business case value for the example in the normalized day-ahead business case graph for the generic battery reference model.

Step 4: Scaling back to the real values

The normalized business case would result in an average profit of 9.71€/MW/h. Since everything is scaled with a factor 1.2, the real business case results in a profit of 11.65€/h or 102.054 €/year.

4 Conclusion

In this document, a novel simplified business case assessment methodology for flexible industrial demand is presented which tries to meet the needs that were formulated in the introduction of this document: time efficiency, cost effectiveness, no specific need for modelling and optimization knowledge and a limited loss in accuracy as a trade-off is considered acceptable.

The document presents a basic concept of “pre-calculating” the business case value of a number of reference processes which are presented in graphs. By means of mapping, normalization, and scaling, a limited number of pre-calculated reference business cases is used as a basis for the business case calculation of a much broader set of real industrial processes.

The document is non-exhaustive neither from the point of view of the covered business cases, target countries nor reference processes. Markets and regulatory frameworks evolve over time and so do possible business cases. The main objective of this report is to clearly illustrate the approach and the possibilities of the concept by means of a number of example processes and example business cases. The methodology may be further extended during the case studies which will be performed in WP4 of this project. Normalized reference graphs for a particular target country will be generated when a case study in that country takes place as far as public price information is available. Extension of the reference models are possible within or after the project depending on the specific application for a particular case study. By doing so, the library of the reference models can be extended in the future.

Have the needs been met?

Under the condition that the industrial process can be mapped on a relevant reference process, the proposed methodology is very straightforward and boils down to some basic normalization, scaling and looking up a value in the correct business case graph which is definitely time efficient, cost effective and for which there is no need for any optimization knowledge. From a tool design point of view, the most challenging task is the selection of a good set of reference processes. From a tool user point of view, the most challenging aspect will be the mapping of a real process on reference processes.

Can a complex industrial process be mapped on a simple reference process? Usability.

It is impossible to conceive simplified reference processes which can handle the most complex industrial processes. Industrial processes, however, are quite often an interconnection and combination of underlying sub-processes where the complexity is caused by dependencies and constraints of the interconnections and not so much by the intrinsic complexity of the sub-processes itself.

Figure 24 shows an example of an industrial process consisting of 6 underlying interconnected sub-processes where only “Process 4” and “Process 6” have demand side flexibility. In order to do a correct business case calculation, an overall model should be constructed because the use of the flexibility in “Process 4” will influence the constraints of the flexibility in “Process 6” via “Process 2&5”. Constructing such overall complicated model is often a time consuming and complex task.

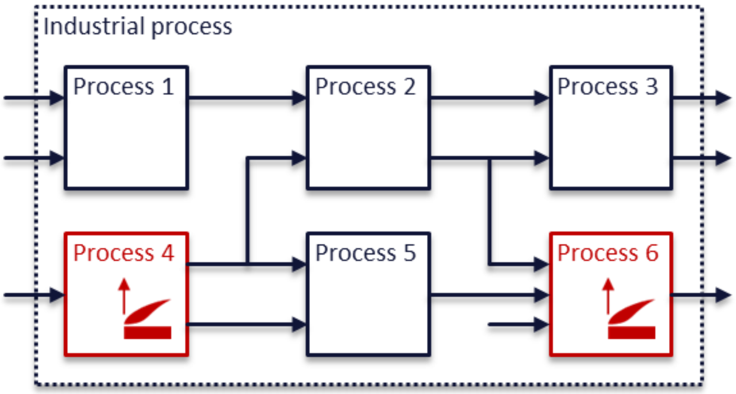


Figure 24: Example of an industrial process consisting of 6 underlying interconnected sub-processes

An alternative, methodologically simpler, approach could be to only consider the 2 flexible processes (4 & 6) and consider them as individual, independent processes. The inputs and outputs are chosen as good as possible and individual business case values are determined. Due to the fact that the individually considered processes are in general less restricted compared to the real industrial process, the sum of the individual business case values is an overestimate of the real business case value. Nevertheless, this can still be very valuable information because it sets an upper boundary for the expected business case value. In case the sum of the individual business case values does not meet a minimum threshold to justify e.g. investments in demand side flexibility, this information is sufficient to make a decision.

While the probability is quite small that a whole industrial process can be mapped on a simple reference process, it is more likely that this approach works on simple sub-processes.

Accuracy

The simplified assessment methodology is derived from the “Adapted methodology for optimal valorization of flexible industrial demand” as described in [3]. Because of the simplification step of an initial fully detailed starting point, by definition the accuracy can never be better than the starting point. Under the assumption that a perfect mapping between the actual process and the reference process is possible, the simplified assessment methodology will deliver the same level of accuracy as the original method.

This means that the obtained business case value is the best case value which provides an upper bound on the maximum achievable value for the given business model, based on historical data without taking opportunity costs into account.

Further, the simplified methodology relies on the availability of public data. Specific and confidential price information which can only be achieved during the discussion with the plant owner can be integrated in a custom made model and optimization but cannot always be used in the simplified assessment methodology. In some cases, like the ToU business case example in section 3.3, there is a linear scaling of the business case value with the price difference between peak and off-peak and a correction can be made after the business case graph is generated. However, such solutions cannot be considered as a general rule to compensate for a possible lack of public data.

Further, the simplified assessment methodology does not support combined business cases. However, a same approach can be used as explained before: the sum of the business case values of 2 or more business cases will always be more than the real value of the combined business case and sets an upper bound to the expected value.

Design for flexibility

Today, the focus is mainly on finding demand side flexibility in existing industrial estates. Due to the growing amount of renewable energy sources and an encouraging role for Flexible Industrial Demand in European policy making [7], it is expected that future energy intensive industrial plants will take the economic value of flexibility into account already during the design phase of a new plant. Normalized business case graphs are well suited to support design decisions. This is illustrated by means of an example.

Example:

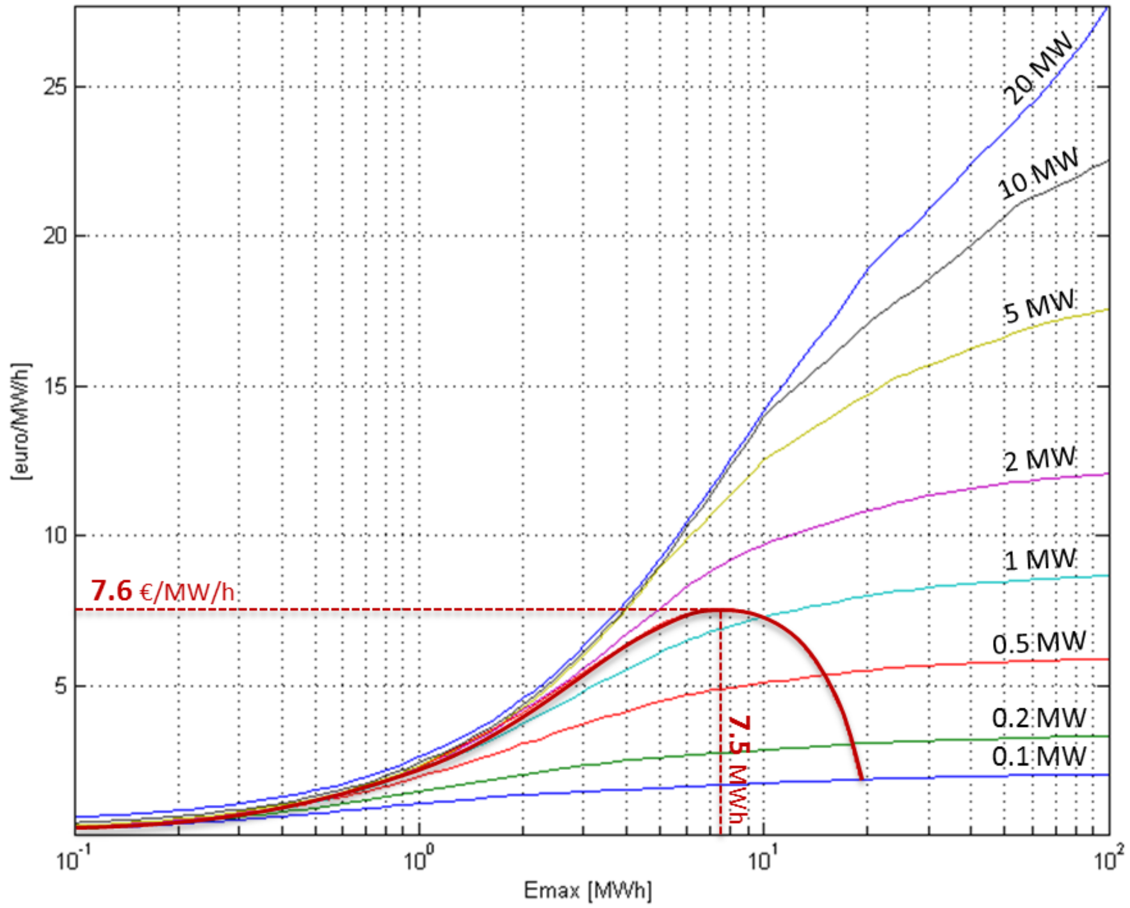


Figure 25: Normalized day-ahead business case graph with constant investment line for optimal design support.

During the design phase of a buffered industrial process (as shown and discussed earlier in Figure 2) the buffer size and the modulation flexibility (Pmax-Pmin) of the process before the buffer still have to be determined. The company will source its electricity from the day-ahead market and the question is how modulation flexibility and buffer size should be chosen in order to make a maximum profit on the day a-head market. It is clear that when the first part of the process is very flexible, but the intermediate product cannot be stored in a buffer, there is no flexibility and consequently no profit. The other way around doesn't work either: a large buffer doesn't make sense if the input and output rates are both constant. Which combination results in the most optimal business case keeping in mind that the buffer size costs 5.000 €/MWh, the flexible power costs 50.000 €/MW power and total investment cost should not exceed 100.000 €?

The optimal combination can be determined from the normalized day-ahead business case graph. On top of the normalized day-ahead business case graph, as shown in Figure 25, an equal investment line (red bold) is plotted. The line represents all combinations of power and buffer size with a total investment cost of 100.000 €. At the left hand side of the equal investment line, the buffer size is 0.1 MWh and the flexible power is 1.99 MW resulting in a total investment cost of 0.1[MWh] x 5.000[€/MWh] + 1.99[MW] x 50.000[€/MWh] = 100.000 €. At the right hand side of the equal investment line, the buffer size is 19 MWh and the flexible power is 0.1 MW resulting in the same total investment cost of 19[MWh] x 5.000[€/MWh] + 0.1[MW] x 50.000[€/MWh] = 100.000 €.

The equal investment line confirms that there exists an optimal combination: A buffer size of 7.5 MWh and 1.25 MW flexible power result in the best business case for the day-ahead market. This ratio might be different when another business case would have been selected.

Scaling up to a commercial tool

This document shows the concept of a novel simplified approach to determine the economic value of flexible industrial demand in different business cases. Based on the information collected in [3], it has the potential to calculate the most relevant business cases for demand response in the IndustRE target countries. In this document, the results of the pre-calculated business cases are presented in graphs but this could possibly be organized differently in a commercial software tool. The results could be organized in a spreadsheet or web based GUI which can offer additional support in normalizing and scaling of the input data, and correct interpolation in the available data. Such tool could also foresee support in mapping actual industrial processes on normalized reference processes. During a number of case studies, which will be performed in the IndustRE project, further insight will be achieved in the usability and the potential gaps of the simplified assessment methodology which could also be used to refine the needs of a commercial tool. A commercial tool development itself is beyond the scope of the IndustRE project but the actual needs and target audience for such commercial tool will be further investigated in the IndustRE project in Task 3.4: “Knowledge transfer to commercial consultancy agencies”.

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